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Yield-Water Relationships of Summer-Fallowed Winter Wheat

A Precision Study in the Texas Panhandle

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Yield-Water Relationships of Summer-Fallowed Winter Wheat

A Precision Study in the Texas Panhandle

By Wendell C. Johnson and Ronald G. Davis[1]

ABSTRACT

In a 10-year study (1968-77), special techniques, including minor land leveling and the use of a rolling platform while taking neutron readings, were used to increase the reliability of soil water determinations. The maximum amount of stored soil water that 'Tascosa' wheat, *Triticum aestivum* L., used from Pullman clay loam, the premier soil of the Texas High Plains, was 7 inches, and the maximum depth of extraction from the soil was 6 feet. A close relationship ($r = 0.97$) occurred between total water use (soil water plus growing season precipitation) and wheat yield. The average yield increase was 2.41 bushels per acre per extra inch of total water used. The average yield increase was 2.70 bushels per acre per extra inch of soil water extracted and 2.22 bushels per acre per extra inch of growing season precipitation. Statistical analyses showed, however, that growing season precipitation was of the greatest overall importance in determining yield. Total water use by individual crops ranged from 4.1 to 21.9 inches for yields ranging from 10.5 to 51.4 bushels per acre. Tillage frequency ranging from infrequent (once before and once after simulated chemical fallow) to 1.4 times normal or conventional tillage frequency had a negligible effect on grain yield and protein content. Favorable water conditions in the fall were highly important in enabling some crops to develop an efficient root system and endure long periods of winter and spring drought. Under favorable conditions, some crops extracted water to a depth of 6 feet in the soil and left no available soil water at harvest. Following a dry fall, other crops extracted soil water to a depth of only 3 feet and left unused as much as 4.25 inches of available soil water at harvest. Little water was conserved by fallowing during the summer months. Most water was stored when there was accumulation from fairly heavy rains in late spring or early fall. Index terms: chemical fallowing, neutron-scattering method, precipitation, Pullman clay loam, soil water, summer fallowing, tillage frequency, *Triticum aestivum* L., winter wheat.

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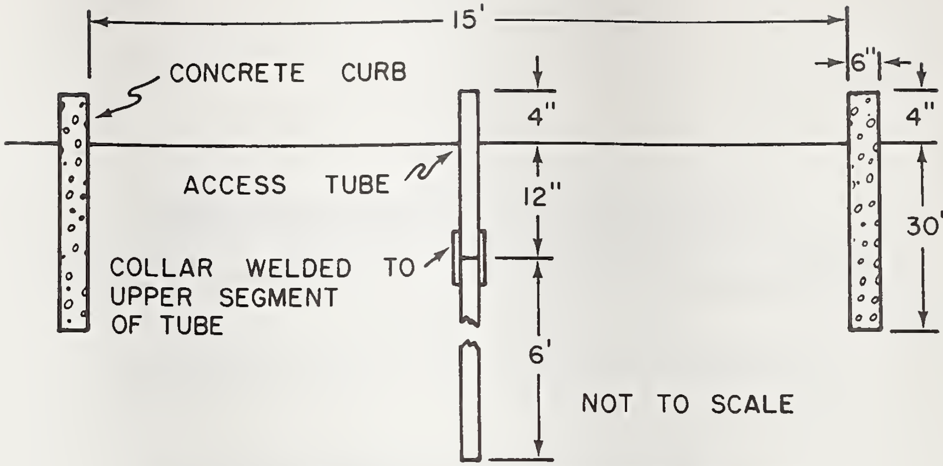

FIGURE 1.—Arrangement of plot curbs and neutron meter access tubes.

INTRODUCTION

In climatic areas where summer-fallowed winter wheat is grown, a discussion of the important features of the summer-fallowing and crop-growing seasons inevitably focuses on water because water is almost always the limiting factor in crop production. Water can be considered from the standpoint of the amount and distribution of precipitation, the fluctuations and causes of fluctuation in soil water, and the relationship between soil water availability and crop yield.

Difficulty in measuring soil water content has long been a major obstacle to progress in studying dryland crop production. For many years the method most commonly used was the gravimetric method, in which the water content was determined by weighing soil samples before and after drying in an oven. This method was laborious and, because of the inherently great variability in dryland soil water, the number of samples needed to obtain a significant result was often prohibitive. The neutron-scattering method, which came into general use about 1960, promised to free researchers from the limitations of the gravimetric method. The neutron-scattering method samples a larger volume of soil and is nondestructive to it, so soil water readings can be repeated on the same volume of soil. This is an advantage, especially in studying changes in soil water content, because it reduces the effect of soil variability. Calculations based on probability theory have shown that to obtain a comparable level of precision with the two methods, 7 to 50 times as many gravimetric soil samples as neutron readings are required (Van Bavel 1963). With the neutron meter, it is possible to make a "custom" determination of the minimum points of exhaustion of soil water for each sampling location. Minimum-point data are needed to determine plant-available water (Mathews and Cole 1954). With gravimetric soil water measurement, an average laboratory-determined, minimum-point value must be used for all sampling locations.

The neutron-scattering method, however, also has objectionable features. The escape of neutrons across the soil-air interface causes an underestimate of soil water when readings are made near the soil surface (Pierpoint 1966). Compaction of the soil and damage to the crop when taking neutron meter readings are hard to avoid. The neutron meter access tubes also cause an unnatural soil condition by interfering with cultivation when field-size implements are used.

This report presents results of a 10-year study (1968-77) of the effects of soil water availability, precipitation, and tillage frequency on the yields of winter wheat, *Triticum aestivum* L., grown on summer-fallowed land. A major goal in designing this study was to devise improved techniques for measuring dryland soil water. We attempted to attain this goal by making conditions as favorable as possible for using the neutron meter.

Differing levels of tillage intensity during the summer-fallowing period before seeding of winter wheat in the fall were the experimental treatments in the study. Over the years, the trend in dryland farming in the Great Plains has been toward reduced tillage intensity. The dust mulch concept

FIGURE 2.—Plowing of test plots with garden tractor before seeding of wheat. Lighter colored plots are chemically fallowed plots.

gave way to tillage with the moldboard and one-way plows, which in turn were succeeded in the 1930's by stubble-mulch tillage with large sweeps. Currently, great interest is being shown in minimum tillage, which finds its ultimate expression in chemical fallow. At the opposite extreme of tillage intensity is the opinion still held by some farmers that, for maximum conservation of soil water during the fallowing period, each significant crust formation after a rain needs to be broken, even though cultivation at the time may not be needed to control weeds.

EXPERIMENTAL DESIGN, METHODS, AND MATERIALS

Soil Series and Test Plots

The study was conducted from 1968 through 1977 at USDA's Southwestern Great Plains Research Center, Bushland, Tex., 12 miles west of Amarillo. The soil there is Pullman clay loam,[2] which is described in the National Cooperative Soil Survey as a member of the fine, mixed, thermic family of Torrertic Paleustolls. The upper 18 inches are sticky and plastic when wet and form a hard crust in drying. This soil is calcareous below a depth of 18 inches, and caliche occurs at a depth of 48 inches. It is well drained and has slow runoff and very slow permeability.

[2] Formerly a member of the Reddish Chestnut great soil group.

FIGURE 3.—Seeding a block of test plots with a 16-10 single-disk drill. Access-tube extensions were not removed and are visible in center of block; note seeded buffer area on either side of block.

There were two blocks of test plots, one in fallow and the other in wheat in a given year. The plots were small, 15 by 20 feet, and were alined end-to-end so that each block of nine plots (three replications times three treatments) was 15 by 180 feet. Each block of plots was bordered on two sides by a 6-inch-wide reinforced concrete curb that extended 4 inches above ground and 30 inches into the soil (fig. 1). The curbs served to support a rolling platform, which was used when making neutron meter readings, and also as a reference plane for keeping the soil surface flat and level. The experimental area was located on a divide between two distant playa lakes so that there would be no tendency for surface water to cross the plots. Two neutron access tubes made from 1.5-inch-diameter, thin-walled, galvanized-steel electrical conduit were installed in each test plot; each tube consisted of two sections. The lower section was 6 feet long and was installed with its upper end 1 foot below the soil surface in a hole made with a soil coring machine. The upper, shorter section had a collar on its lower end that slipped over the upper end of the longer section. The shorter section or "extension" was 16 inches long and extended 4 inches above the soil surface (fig. 1). Removing the extensions allowed the plots to be tilled with a field-size stubble-mulch plow.

Seeding and Harvesting

Just before seeding, all test plots were

FIGURE 4.—Combine-harvesting of wheat from block II test plots in 1973. These plots had a record-breaking average yield of 51.4 bushels per acre. Four center rows were hand-sampled for yield.

FIGURE 5.—Plowing a block of test plots after wheat harvest.

cultivated with a two-wheeled, walking-type garden tractor equipped with two 18-inch sweeps (fig. 2). The plots were seeded with the 'Tascosa' variety of winter wheat, *Triticum aestivum* L., at the rate of 30 pounds per acre, using, depending on certain conditions, either a single-disk drill with 10-inch rows or a hoe-type deep-furrow drill with 13.5-inch rows. The 10-inch rows were considered most suitable for the small-size plots. However, the hoe-type drill was given preference when deep placement of seed was necessary because of a shortage of water near the surface or when there was a large amount of surface residue. To avoid disturbing the soil, the access-tube extensions were not removed for the seeding operation (fig. 3). A buffer area 27 feet or more wide was also seeded around the perimeter of the block of plots.

Yields of wheat straw and grain were determined by hand-harvesting four 20-foot-long center rows of each plot. The samples were threshed with a small-plot thresher. The straw removed from the plots was returned to the plots after threshing. After being sampled for yield, the remainder of each plot was harvested with a field-size combine (fig. 4).

FALLOWING PERIOD

Immediately after harvest (at the beginning of the fallowing period) the access-tube extensions were removed, and all the test plots were plowed at a depth of about 5 inches with a field-size sweep machine having 30-inch sweeps (fig. 5). This was the only time during the 15-month fallowing period that the access-tube extensions were removed, since removing the extensions usually disturbs the natural soil condition. However, tilling after harvest usually leaves the soil in a hard, dry, cloddy condition, so the effect of removing and replacing the extensions at this time is negligible. The remaining cultivations after harvest were made with the garden tractor and were supplemented by hand tillage with a scuffle hoe.

TILLAGE TREATMENTS

There were three experimental treatments, consisting of the following levels of tillage frequency:

T_1—Conventional, plots tilled an average of about seven times during the 15-month fallowing period.

T_2—Frequent, plots tilled when significant soil crusts formed; tillage frequency averaged 1.4 times that of T_1.

T_3—Infrequent (chemical fallow), plots tilled twice per fallow period, once just after harvest and once just before seeding. Interim weed control by

FIGURE 6.—Making soil water measurements with neutron meter from rolling platform.

FIGURE 7.—Making soil water measurements while using extensions beneath undercarriage of rolling platform.

spraying with paraquat,[3] a low-residue contact herbicide, at the rate of 1 pound per acre.

SOIL WATER MEASUREMENT

The rolling platform straddled the test plots and enabled soil water measurements to be made with the neutron meter whenever desired, under any soil condition, without disturbing the plot area (fig. 6). Extensions were added to the undercarriage of the platform as needed to elevate it above the wheat and thus avoid damage to the crop (fig. 7). The general schedule for measuring soil water was weekly from March 1 until harvest, when the plots were in wheat (on about 17 or 18 dates in all); monthly, when the plots were being summer-fallowed; and monthly from seeding until weekly sampling began after March 1. A shield count was made at the start of taking neutron readings in each plot. The average of the nine resulting shield counts per block of plots was used in all calculations of soil water contents for that block of plots on that sampling date. At each access tube, measurements were made with the effective center of measurement of the neutron probe at the midpoint of successive 1-foot layers of soil, starting at a depth of 6 inches and ending at a depth of 6.5 feet[4]. This resulted in a total of seven readings per access tube.

At the midpoint of the second and deeper 1-foot layers of soil, the soil water content was calculated by using a formula determined from three secondary reference standards provided by the manufacturer of the neutron meter and probe. The reference standards were similar in construction to the probe shield (visible in fig. 7) and contained varying amounts of the hydrogenous material polyethylene, which gave neutron count rates corresponding to varying levels of soil water content. The shield itself served as a fourth standard. The factory-determined standard values were modified slightly to agree with the results of field experience at the Research Center. The formula expressed water content as a function of the count ratio, which is the ratio of the count rate with the probe in the soil to the count rate with the probe in the shield.

Use of the neutron meter in the top foot of soil is a special problem because of loss of neutrons into the atmosphere through the soil-air interface (Pierpoint 1966). A special formula was derived for use in calculating the water content of the top foot of soil from data obtained on ten dates during 1972 and 1973 that covered a wide range of soil water contents. Data for deriving the formula came from a series of 18 pairs of water determinations made on each sampling date. One of each pair was made with the neutron meter at the 6-inch depth in an access tube in an experimental plot, and the other was made gravimetrically a few feet away at a comparable location in the buffer area. The average of the gravimetric determinations made on a certain date was considered to be the true soil water content.

[3] 1, 1'-dimethyl-4,4'-bipyridinium ion.

[4] We used a model 1651 scaler, a model 105A probe with a 100 millicurie Am-Be source, and a model S-6A shield manufactured by Troxler Electronics Laboratories, Triangle Park, N.C.

In actual practice, the routine followed was to calculate soil water contents for all depths by using the same basic equation, after which a correction was applied to the top-foot amounts. The basic equation was

$$H_2O_{(2\text{-}7)} = -0.91 + 7.24R, \qquad (1)$$

where H_2O is water content in inches per foot of depth and R is the count ratio. The subscript (2-7) means that the equation applies without correction from the second to seventh foot-layers of soil.

Figure 8 indicates the relationship between the average water content in the top foot of soil measured gravimetrically and that measured with the neutron meter and calculated by using equation 1. The ten plotted points cover a range of soil water contents, from the minimum point to the field carrying capacity of the soil. The relationship is

$$H_2O_{(1)} = 0.80H_2O_{(2\text{-}7)} + 0.95, \qquad (2)$$

where $H_2O_{(1)}$ is the true water content in inches of the top foot of soil and $H_2O_{(2\text{-}7)}$ is the water content of the top foot of soil calculated by using the basic formula (equation 1). If equation 1 were used to compute top-foot soil water without correction, there would be an underestimate of water content of about 32 percent at the minimum point but only 3 percent at the field capacity (fig. 8). This occurs because the neutron meter samples a smaller effective volume of wet soil than of dry soil, and fewer neutrons are lost to the atmosphere. The minimum point and field capacity of the top foot of this soil are 12 and 26 percent on the dry-weight basis, respectively. The bulk density of the top foot of soil was assumed to be 1.5.

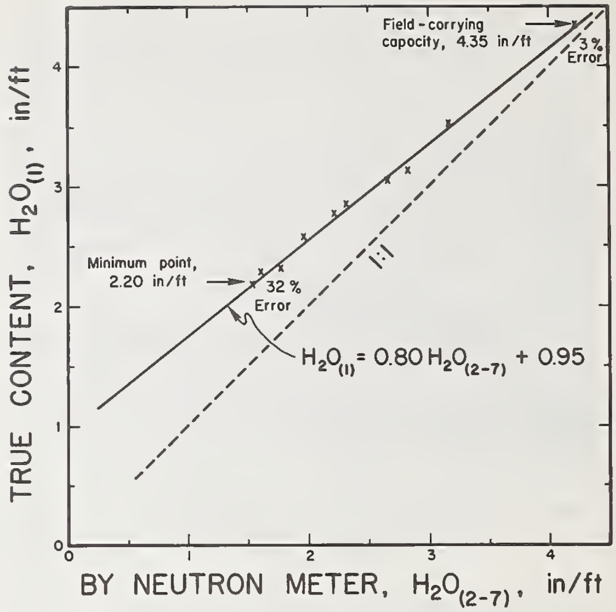

FIGURE 8.—Relationship between true water content of top foot of soil measured gravimetrically and that measured with the neutron meter at 6-inch depth and calculated by using equation 1.

MINIMUM POINT OF EXHAUSTION

Soil water content should be expressed in terms of the amount of water available to the plant. Calculating available water requires a knowledge of the minimum point of exhaustion of soil water by the plant. The difference between the minimum point of exhaustion (the "unavailable" water) and the soil's total water content is the "plant available" water. The minimum point of exhaustion is a function of properties of both plant and soil. When determined in the field, it is the quantity of water remaining in the soil when a uniform, well-rooted crop begins to suffer for water. If minimum points are based on laboratory determinations made on samples of soil, it is necessary to use average values. This can lead to large errors because of soil variability. One advantage of the neutron-scattering method is that a custom profile of unavailable water can be determined by direct observation for individual neutron meter access tubes, thereby allowing for soil variability.

The minimum point data shown in figure 9 for the access tubes of block I test plots help to illustrate the extent of soil variability that can occur in a distance of less than 200 feet in Pullman clay loam, which is considered to be a relatively uniform soil. Two well-rooted wheat crops near harvest in 1970 and 1972 provided suitable conditions for obtaining the minimum point of exhaustion of each 1-foot increment of soil to a depth of 7 feet at each of the 18 access-tube locations. The amounts of total unavailable water in 7 feet of soil varied from 15.26 to 23.06 inches. To give an idea of the magnitude of error that can result from the use of an average value for the minimum point, this 7.8-inch variation in unavailable water is greater than the maximum net amount of stored water (about 7 inches) that we have observed a wheat crop to use from 7 feet of soil during an entire growing season. The high

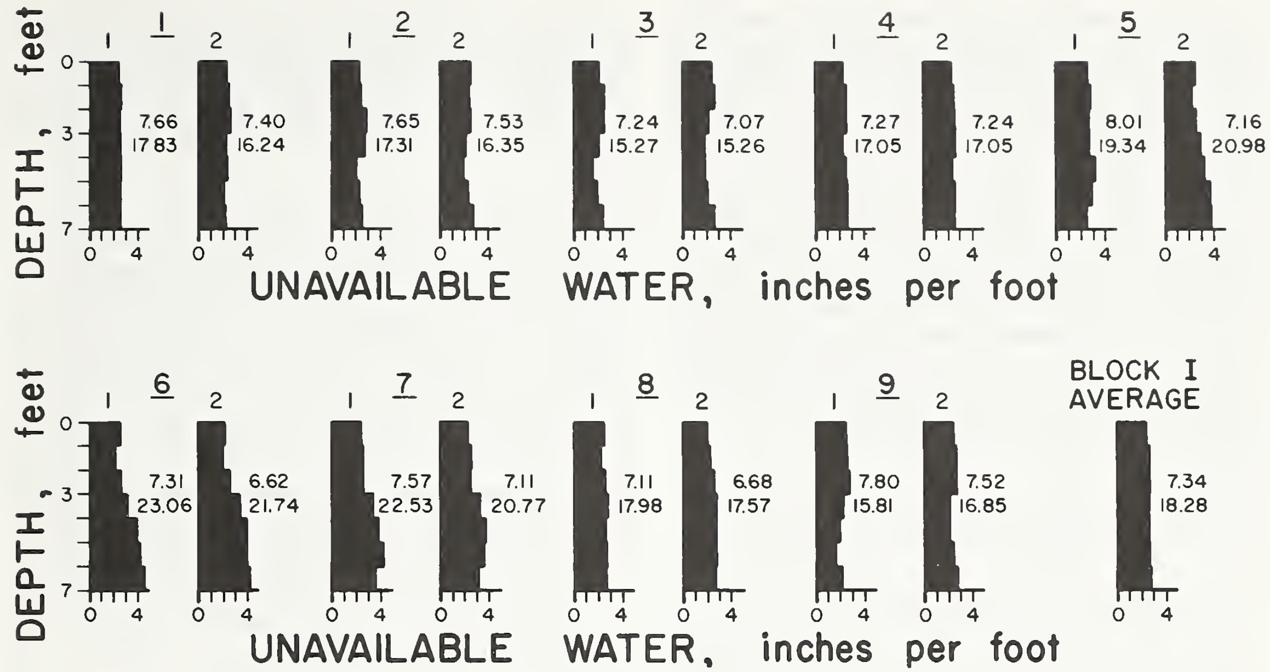

Figure 9.—Profiles of minimum point of exhaustion for individual access tubes of block I, test plots 1-9, and block I average profile. Total inches of unavailable water in the zero- to 3-foot and zero- to 7-foot soil zones are given on right side of each profile.

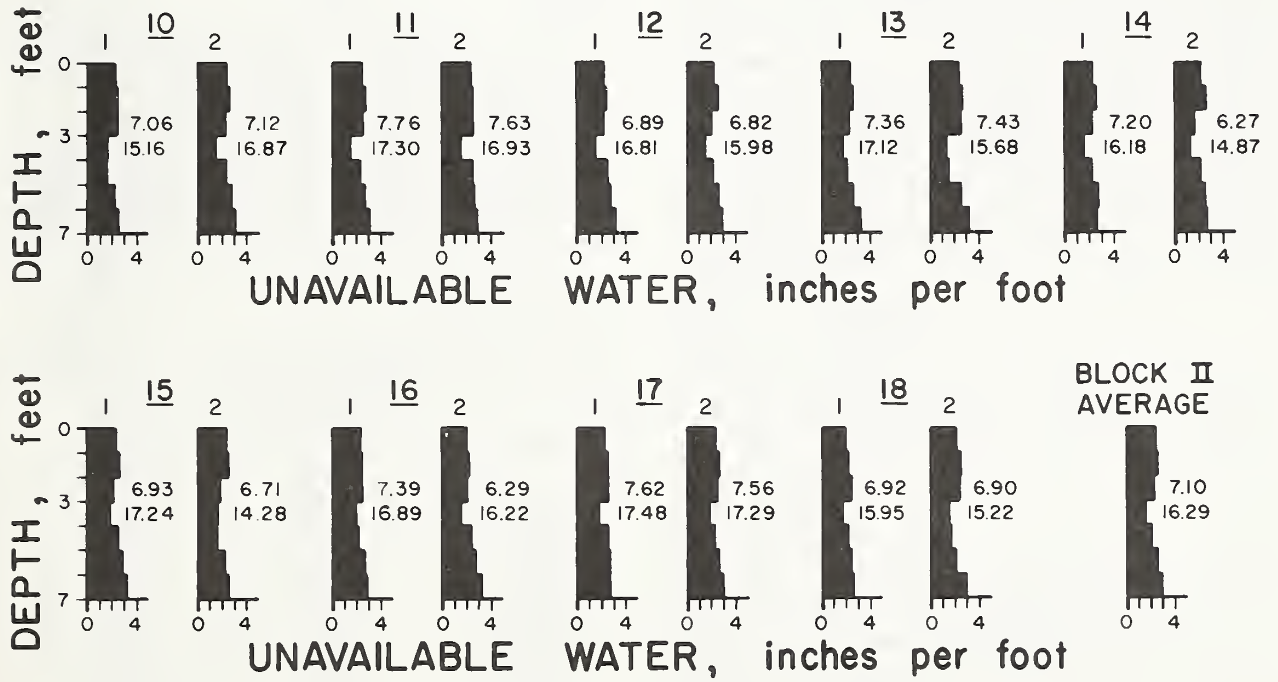

Figure 10.—Profiles of minimum point of exhaustion for individual access tubes of block II, test plots 10-18, and block II average profile. Total inches of unavailable water in the zero- to 3-foot and zero- to 7-foot soil zones are given on right side of each profile.

levels of unavailable water below 3 feet in plots 5, 6, and 7 were associated with gleylike soil material that was first noticed during the ditching process for installation of the concrete curbs. Earlier systematic soil sampling to check the uniformity of the soil failed to detect this irregularity. A good opportunity to establish minimum points for the access tubes of block II test plots did not occur until near harvest of the 1975 crop. Although the block II plots had more uniform subsoil than the block I plots, the variation of total unavailable water at the various access-tube locations was still quite high, 3.20 inches, ranging from 14.28 to 17.48 inches per 7 feet of soil (fig. 10).

RESULTS AND DISCUSSION

The 10-year study is divided into 19-month periods in the discussion of results. Each period begins on June 1 of a year and extends through the succeeding year. Of the two blocks of test plots, one was in fallow while the other produced a crop in any given 19-month period (table 1). A discussion of conditions during a certain period deals first with the block I plots and then with the block II plots. A fallowing period starts after harvest in June of a year and ends about 15 months later at seeding in September or October of the next year. A wheat-growing period starts at seeding in September or October and ends at harvest the following June. Since no two fallowing seasons or growing seasons are exactly alike or are seldom even similar, each is considered separately.

Four illustrations are used in the discussion of each period; figures 11-14 are typical examples. There is a graph showing curves of actual and normal accumulated precipitation for each 19-month period and graphs of the average total available soil water by tillage treatment for the zero- to 3-foot and 3- to 7-foot soil zones of the block I and block II plots. Individual precipitation amounts are indicated on the date they occurred at the bottom of each of these illustrations. The graphs also indicate the dates of harvest (H) and seeding (S). Graphs for each plot in fallow give the dates on which individual tillage treatments (T_1, T_2, and T_3) were plowed (P_1, P_2, and P_3) or sprayed (S_3). For each block of plots that produced a wheat crop, the average yield by tillage treatment is also given. In addition, a chart concerning each block of plots that produced a wheat crop shows the average amount of plant-available water by individual foot-depth increments of soil from January 1 to June 30 as well as dates and amounts of precipitation and harvest date.

As the experiments progressed, it became evident from analyses of variance of results for individual years that, under the conditions of the experiments, the different tillage treatments did not result in differences in yield that were significant at the 5-percent level. For this reason, the discussion of results deals primarily with all-treatment averages, even though curves of average available soil water are shown for each tillage treatment. The results of regression analyses are discussed later, relating the average yield for all tillage treatments in individual years with certain indices of water availability for the crop season. These indices are (1) average total available soil water content at seeding and precipitation during the growing season, as separate independent variables, and (2) total water use (soil water plus precipitation) as a single independent variable.

1968-69

Block I, in fallow.—The plots were continued in fallow, using uniform sweep tillage until they were seeded to wheat in the fall of 1969.

Block II, in wheat.—These plots were seeded to wheat in the fall of 1968. After being harvested in 1969, they were the first to enter into the tillage plan of the experimental outline. The crop was

Table 1.—Blocks of test plots in wheat and in fallow during 19-month periods

Period	Experimental test plots in—	
	Block I	Block II
1968-69	Fallow[1]	Wheat[2]
1969-70	Wheat	Fallow
1970-71	Fallow	Wheat
1971-72	Wheat	Fallow
1972-73	Fallow	Wheat
1973-74	Wheat	Fallow
1974-75	Fallow	Wheat
1975-76	Wheat	Fallow
1976-77	Fallow	Wheat

[1]In fallow in summer of 1969 but different tillage treatments not yet started.

[2]Wheat harvested in summer of 1969.

harvested on June 25, 1969, and the yield averaged 15 bushels per acre, which was slightly below average. Precipitation during the 18 months before harvest was near the longtime normal of 27 inches at Bushland.

1969-70

Block I, in wheat.—Tillage treatments of these plots were not begun until after wheat harvest in 1970. The yields for 1970, therefore, were not influenced by experimental treatment. The block I plots, before being seeded to wheat on September 27, 1969, were in fallow for about 2 years, from harvest of sorghum in the fall of 1967 to wheat seeding in September 1969. The combination of a long fallowing period plus rainfall totaling 1.5 times normal from June 1 to November 1, 1969, resulted in a large amount of stored soil water (fig. 11). The total available water in 7 feet of soil for all plots on November 6, 1969, averaged 7.20 inches, with nearly 5 inches being in the top 3 feet of soil (fig. 12). In most years at Bushland, stored soil water used by a dryland wheat crop comes mainly from the top 3 feet of soil. In exceptionally favorable years, however, as in 1972 and 1975, water may be extracted from as deep as 6 feet. The 1970 crop used the comparatively large amount of 5.70 inches of stored soil water from 7 feet of soil from seeding to harvest, leaving an average of 0.62 inch of unused available soil water in the top 3 feet of soil (figs. 12 and 44, and table 2).

Wheat yields averaged 27.3 bushels per acre in 1970. Although this was an above-average yield, in March, when the crop was making an especially luxuriant growth after the end of the dormant period, it appeared that it might make a record yield of perhaps over 50 bushels per acre, a yield that was realized later, in 1973. However, below-normal rainfall during the spring months was

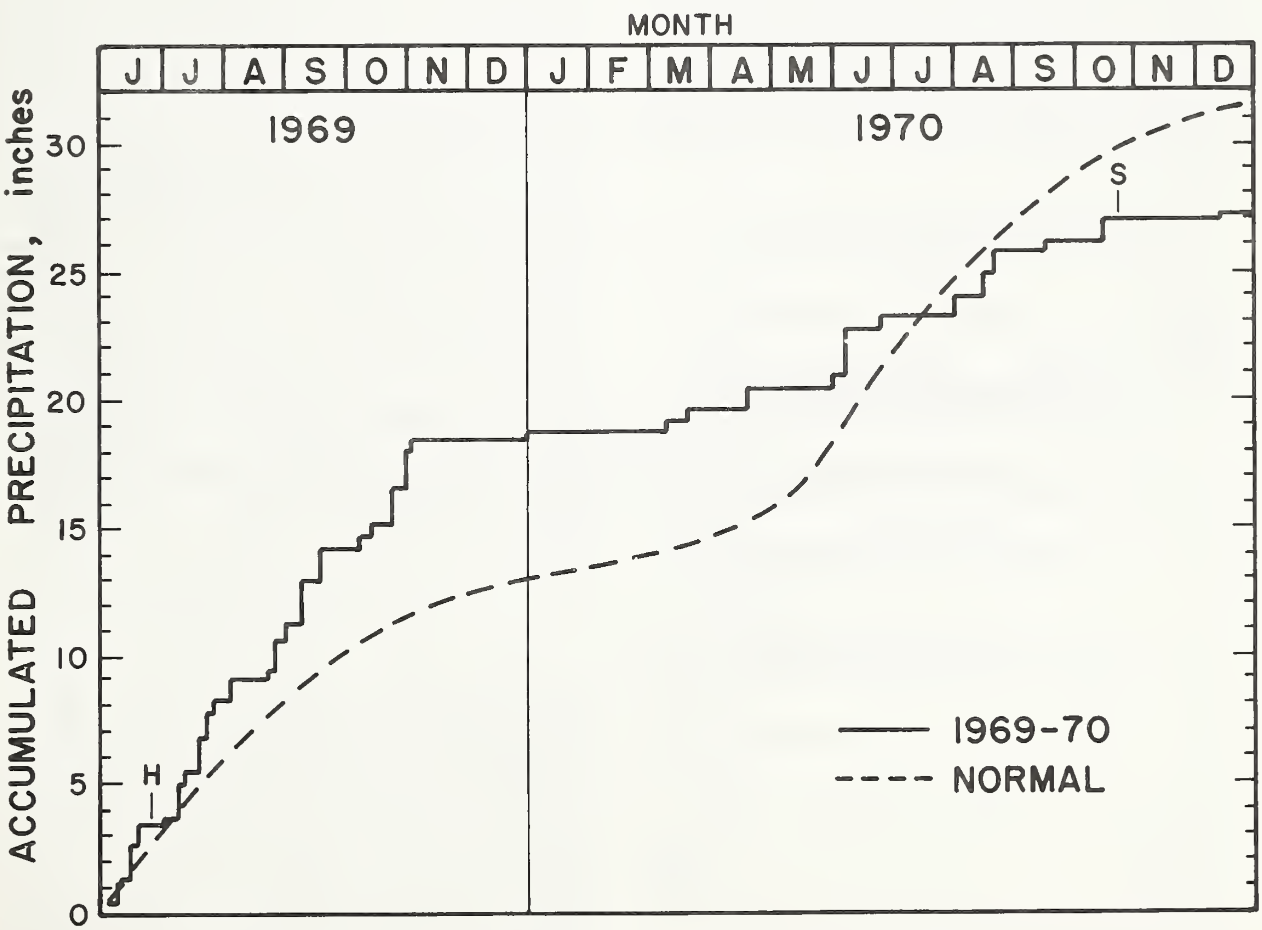

Figure 11.—Normal and actual accumulated precipitation, 1969-70.

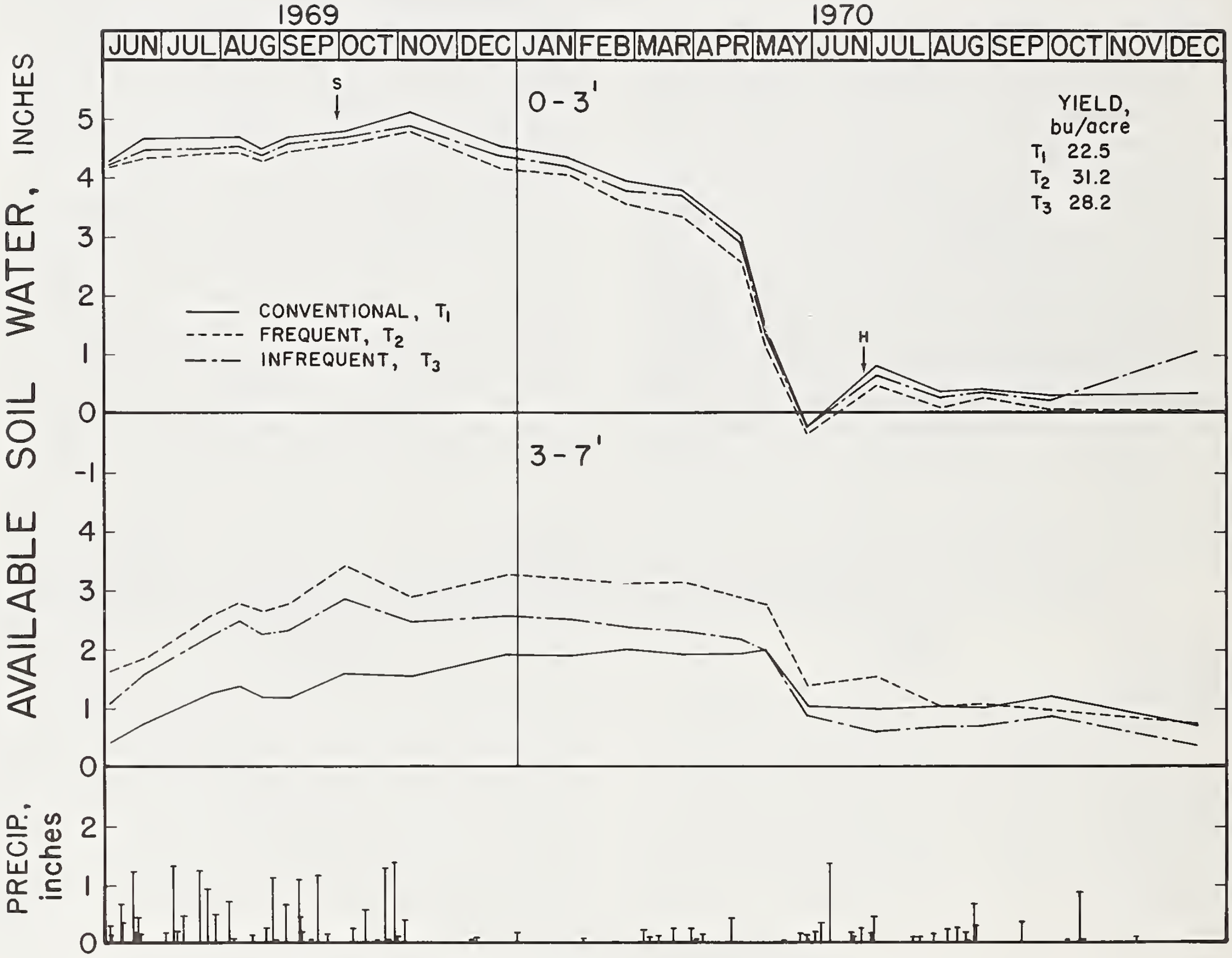

FIGURE 12.—Average available soil water and average crop yield by tillage treatment, block I (in wheat), 1969-70.

insufficient to support the amount of vegetation present, and at the time of the May 27 soil water determinations all available water was gone from the top 3 feet of soil. Apparently, that crop had matured to the point that it was not able to receive much benefit from a 1.30-inch rain on June 8, and too few soil water measurements were being made to closely follow the process of water exhaustion by the plants. In later years soil water readings of plots in wheat were made weekly from March 1 until harvest.

The minimum points of exhaustion for individual access tubes of block I plots were based on observations made in 1970 and 1972. Each of these crop seasons was well suited to making the minimum point determinations because fall rains and plentiful seeding-time soil water favored good rooting and tillering of the crop. Available soil water was present throughout the root zone, and during later growth stages a water deficiency developed that caused the crop to come under water stress. Some judgment is involved in estimating the minimum points, since, given sufficient time, a plant can reduce soil water below the minimum point. As the root system of a crop develops, it can be shown by successive soil water measurements that lower and lower depths of soil become involved in furnishing water to the plant. Therefore, to best determine minimum points for the lower soil depths, it is desirable that the plant first begin to suffer for water as it approaches maturity. Although all available water was removed from the zero- to 3-foot soil zone in 1970, it was later determined from the 1972 data that minimum points of exhaustion were not reached throughout the 3- to 7-foot soil zone. For this reason, the available water curves for the 3- to 7-foot soil zone in figure 12 are shown as being above zero at harvest. A similar situation developed in 1973 when a short water supply in June caused rapid ripening before the deep soil water was completely used.

Figure 13 shows the average amount of available water in individual 1-foot soil layers of the test plots in wheat during the spring of 1970. During May water was being used from a depth of 6 feet. By the first of June, however, the crop was running dangerously low on available water in the top 3 feet of soil. Not enough soil water measurements were made in 1970 to reach a definite conclusion, but it appears that, since no water was removed from below 3 feet after June 1 and grain test weights were below normal, the crop had suffered permanent damage from the drought. This affected its ability to extract soil water.

Block II, in fallow.—During the first 5 months of the fallowing period, June through October 1969, precipitation was 1.5 times normal (fig. 11). The remainder of 1969 was dry and was followed in 1970 by the driest year on record at the Research Center, when only 8.45 inches of precipitation were received compared to a normal of over 18 inches. Good gains in soil water were made from June to November 1969, and on November 6 the average total available water in the zero- to 3-foot soil zone for all test plots reached the high level of 5 inches (fig. 14). This was about the same amount of available water that was in the block I plots at the end of a complete summer-fallowing period (fig. 12). Some increase in soil water in the 3- to 7-foot soil zone occurred during the months of September and October 1969. After November 6, the general trend for the rest of the fallowing period was a gradual decrease in total available soil water in the zero- to 3-foot soil zone and a gradual increase in the 3- to 7-foot soil zone (fig. 14). A seasonal fluctuation in soil water below 3 feet that may be out of phase, both with precipitation and with changes in water level above 3 feet, has often been

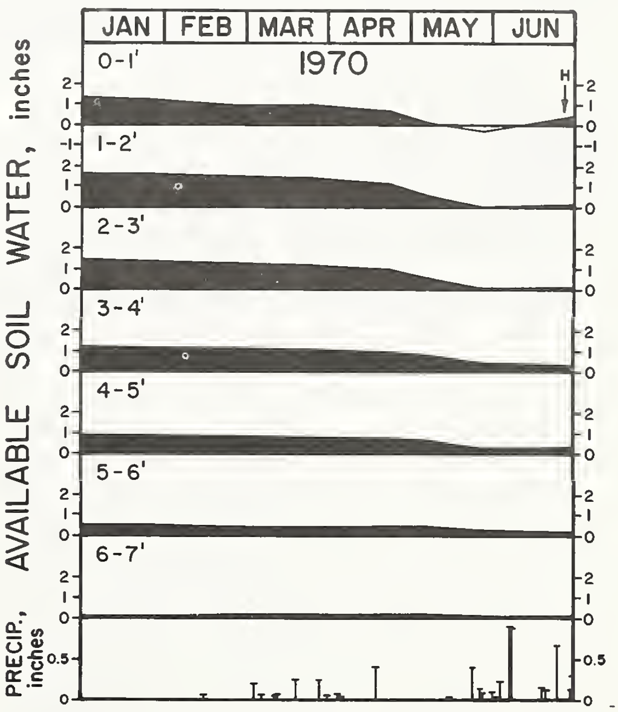

Figure 13.—Average available soil water by 1-foot-depth increments, block I (in wheat), 1970.

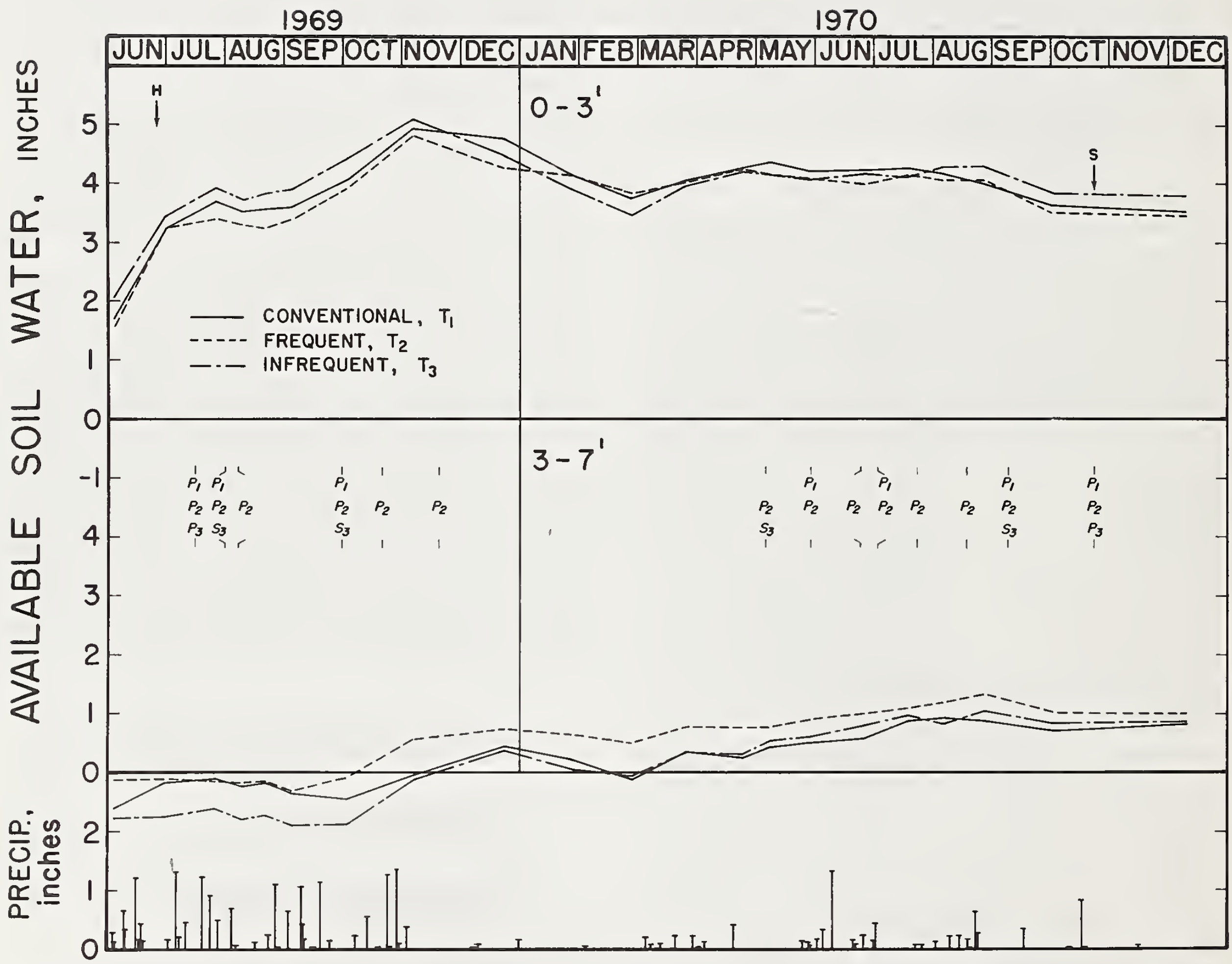

Figure 14.—Average available soil water and plowing and spraying dates by tillage treatment, block II (in fallow), 1969-70.

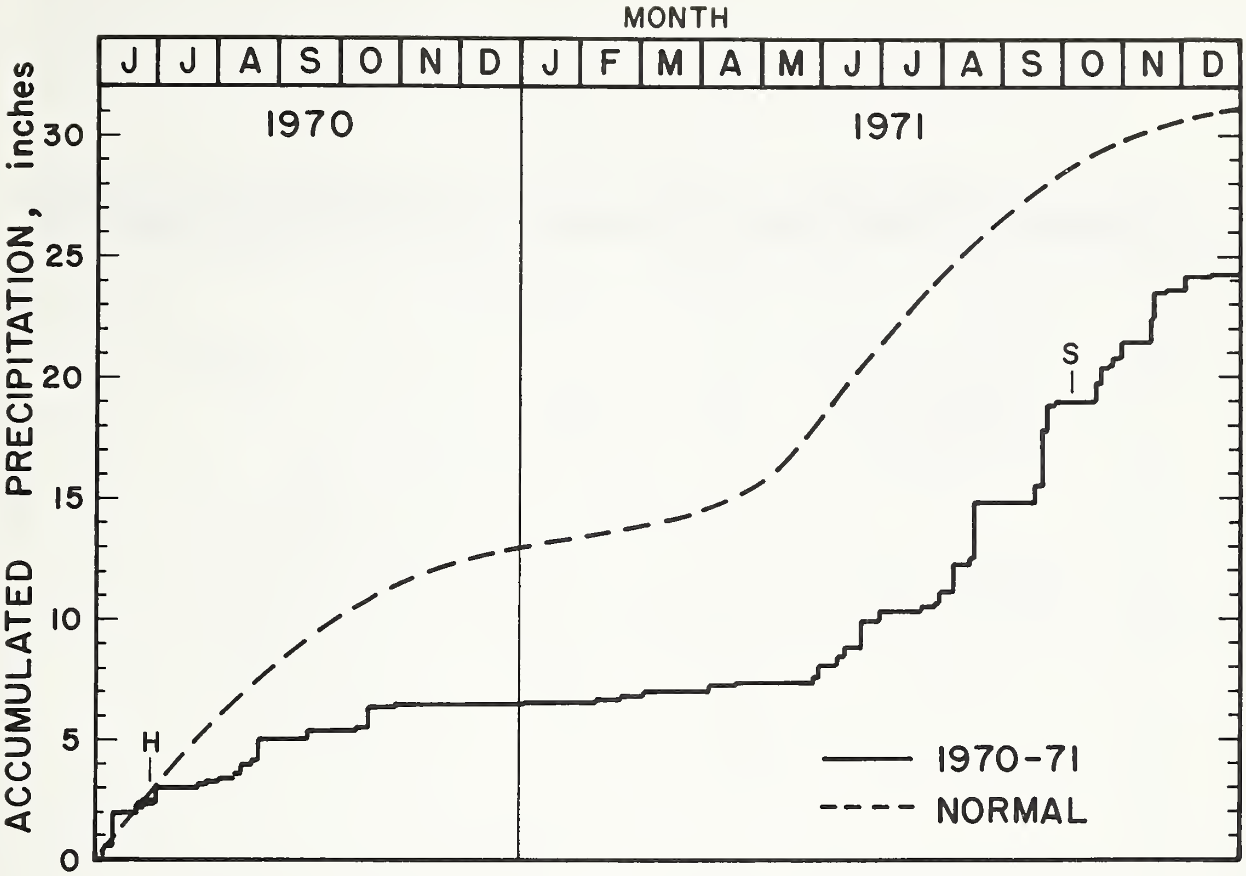

Figure 15.—Normal and actual accumulated precipitation, 1970-71.

observed and its cause has been the subject of speculation. In this experiment, it is not known if the small gain in water in the 3- to 7-foot soil zone was a result of gravitational movement of soil water downward or of upward movement and condensation of water vapor from lower soil layers due to a changing temperature gradient in the soil.

1970-71

Block I, in fallow.—During the dry summer of 1970, the soil water content of the fallowed plots changed very little (fig. 15). Actually, in the top 3 feet of soil there was very little plant-available water to be lost (fig. 16). Ten inches of snow in mid-October added about 0.75 inch of water to the soil profile of the chemically fallowed plots but had little affect on the other treatments. The increase in water on the chemically fallowed plots was caused by snow collecting in stubble which, having received only one cultivation, was more erect than on the other plots. A blizzard on February 20, 1971, left snow equivalent to about 3 inches of water lodged on the fallowed plots, but bare ground was swept free of snow. After this, no additional soil water was gained during the exceptionally dry spring of that year. The surface soil was so dry, in fact, that area farmers were unable to seed dryland grain sorghum until the end of June. The weather trend was reversed in the first half of August when several good rains, totaling about 1.5 inches above the normal for August, were received. Dry weather again returned after August 19, with no additional rain until September 17. Wet weather set in during the last half of September when 4.41 inches of rain were received, which was about 2.75 inches above the normal for September. Wheat seeding was delayed, first by dry soil and then by wet soil, until October 5, 1971. Figure 44 shows that the available water at seeding for the 1972 crop was 6.87 inches.

(*Continued on page 16.*)

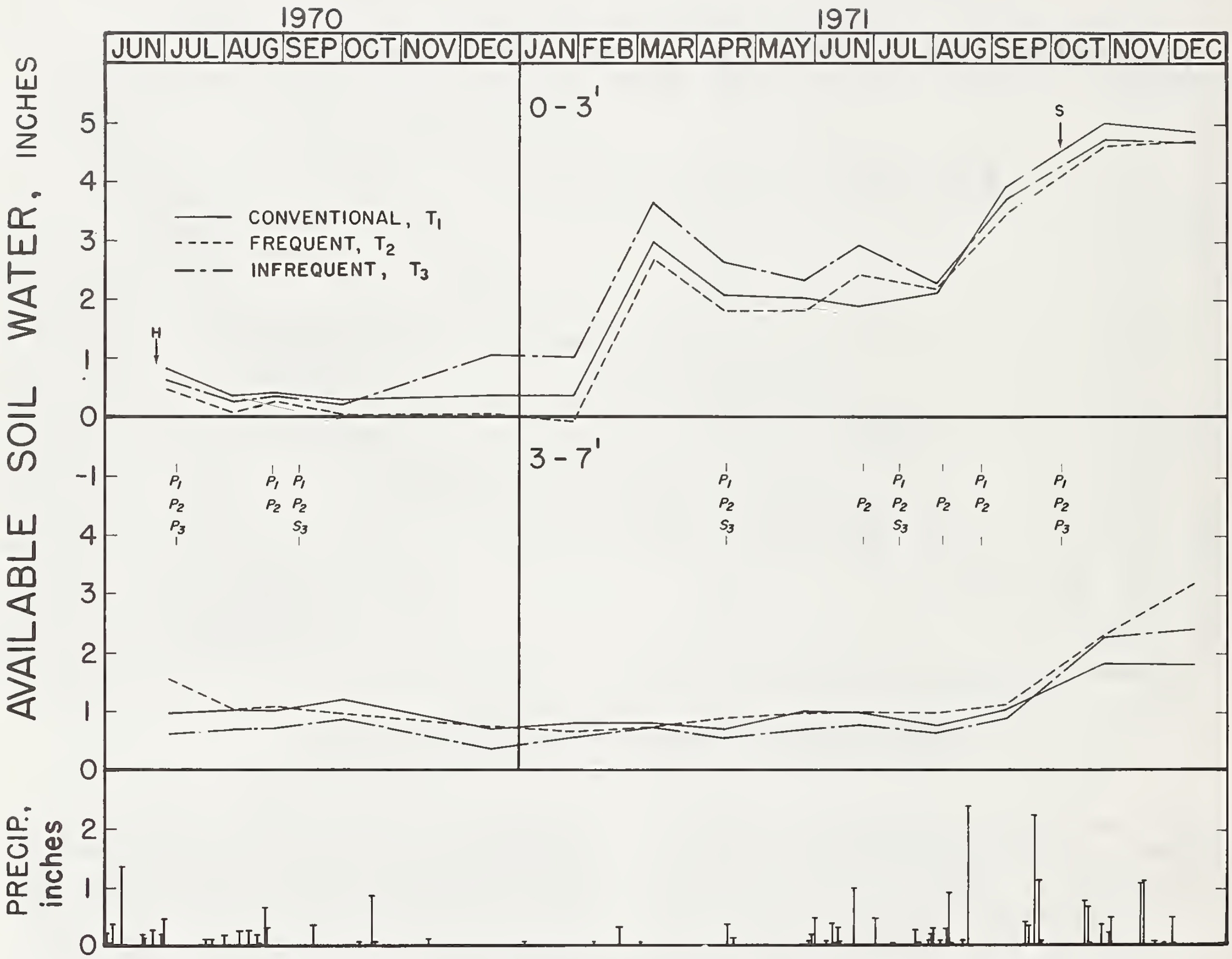

FIGURE 16.—Average available soil water and plowing and spraying dates by tillage treatment, block I (in fallow), 1970-71.

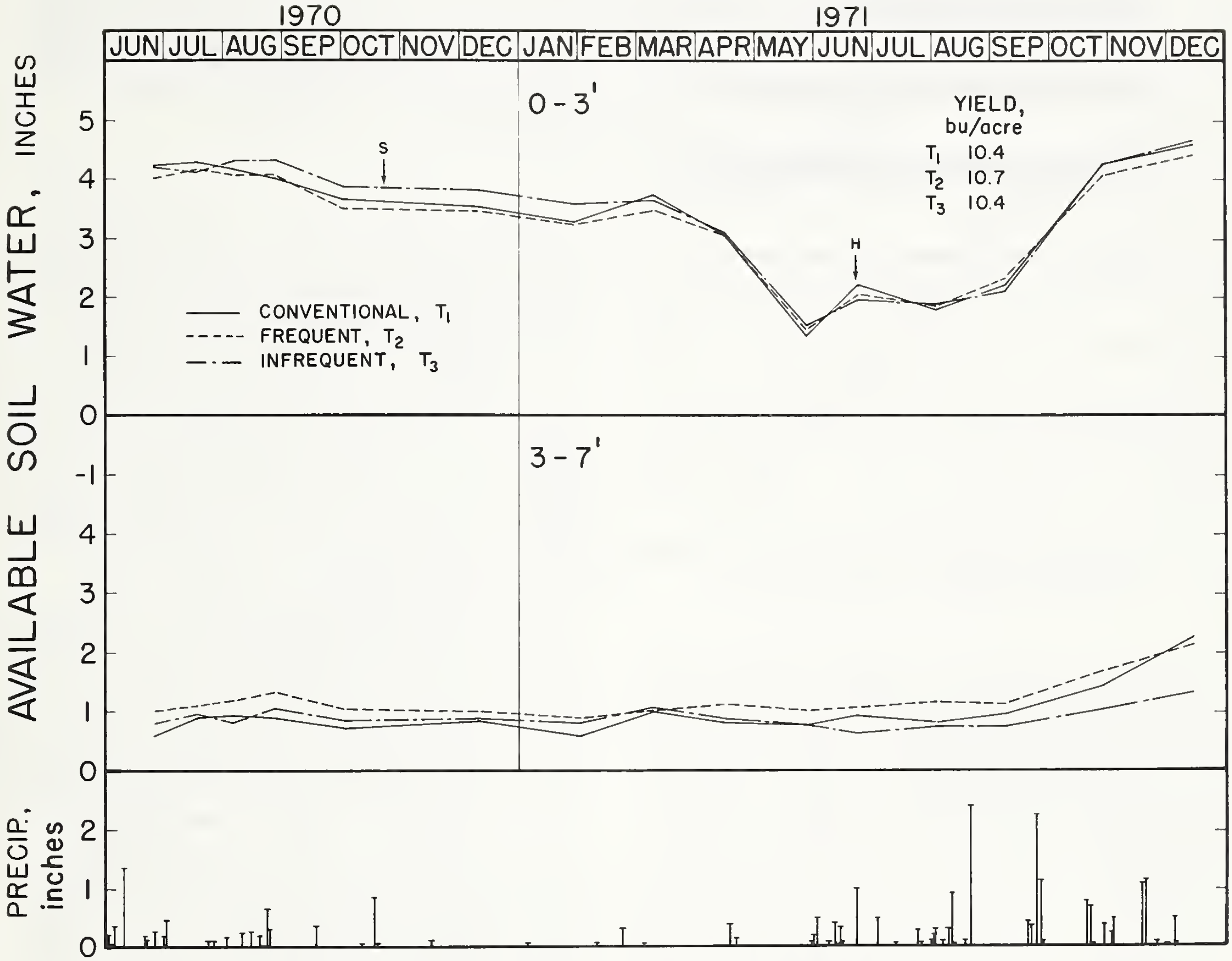

Figure 17.—Average available soil water and average crop yield by tillage treatment, block II (in wheat), 1970-71.

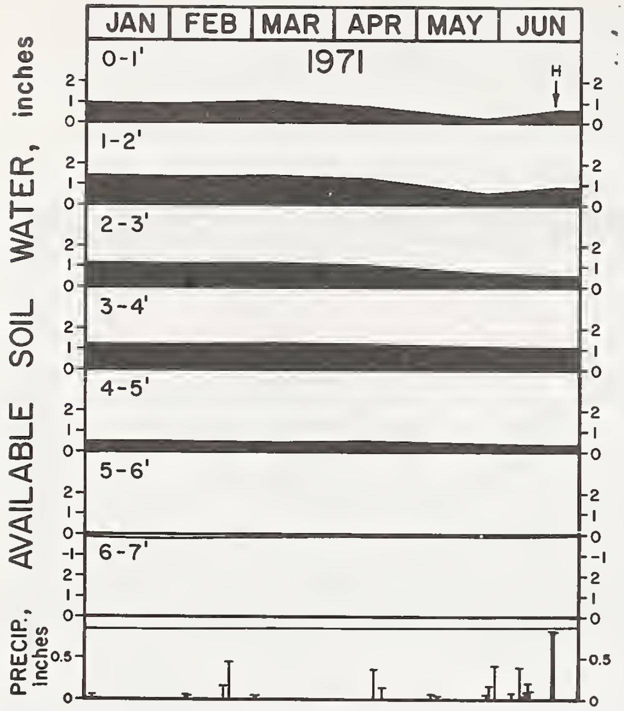

FIGURE 18.—Average available soil water by 1-foot-depth increments, block II (in wheat), 1971.

Block II, in wheat.—Despite the large total amount of available water, the surface soil was too dry for wheat to be planted on the normal date, about September 20, 1970. However, a foot of snow on October 15, the earliest snow on record at the Research Center, provided enough soil water for wheat to be seeded on October 22 (fig. 17). Although a good stand was obtained, root development, tillering, and plant growth in general were very poor because of a combination of almost no precipitation during the 7 months following seeding, lateness of planting, and cool soil temperatures caused by melting of the early snow and an unseasonably early first-killing frost on October 8. (The normal date of first-killing frost is about November 1.) As a result of these factors, the 1971 crop was thin and short, too short on many farmers' fields to be combine-harvested. Only about 1.5 inches of stored soil water were used from the zero- to 3-foot soil zone and 2 inches went unused (fig. 45). The thin stand enabled the crop to endure the drought fairly well, and grain yields on the test plots were better than on most farmers' fields, averaging 10.5 bushels per acre. The straw-grain ratio was 1.57, much lower than the long-time average of 2.0 (table 2).

Figure 18 shows the available water content of individual 1-foot layers of soil under wheat in the spring of 1971. Only limited use was made of available water in the top 3 feet of soil because of the thin stand and poor root development. Gains in water content of the top 2 feet of soil showed that water from rain in May and June was not fully utilized.

1971-72

Block I, in wheat.—For a time in the fall of 1971, it was doubtful if the 1972 crop could be seeded. Frequent rains in July and August had made substantial contributions to the water in the top 3 feet of soil, but they had also brought on a heavy growth of weeds. The weeds and a cultivation followed by a month of hot, dry weather had left the plow layer in a dry, dusty condition as the normal date for seeding winter wheat approached. Fortunately, during the third week of September rains occurred, which made it possible to seed wheat on October 5, 1971.

Although the crop was seeded later than normal, it developed well because of abundant rainfall in October and November (fig. 19). The 7-foot soil profile contained the relatively large amount of 6.87 inches of available water at seeding (figs. 20 and 44). The water was well distributed in the soil with depth, which allowed the crop to develop a vigorous root system. This made possible a second determination of minimum points of exhaustion for the block I test plots the following June. By harvest, the crop had made full use of the original excellent supply of stored soil water. Almost no precipitation was received from early December to mid-May (figs. 19 and 20). This forced the crop to live almost entirely on stored soil water. The crop gradually deteriorated because of water stress until, on May 1, it appeared that it would be a complete loss if rains did not come very soon. Highly opportune rains did occur, and the crop was able to make good use of the water. The crop that seemed likely to yield only 5 bushels per acre yielded an average of 31.5 bushels per acre. Yields ranged from 27.9 bushels per acre for the T_1 treatment to 36.7 bushels per acre for the T_2 treatment. It is interesting to note that the average yields by tillage

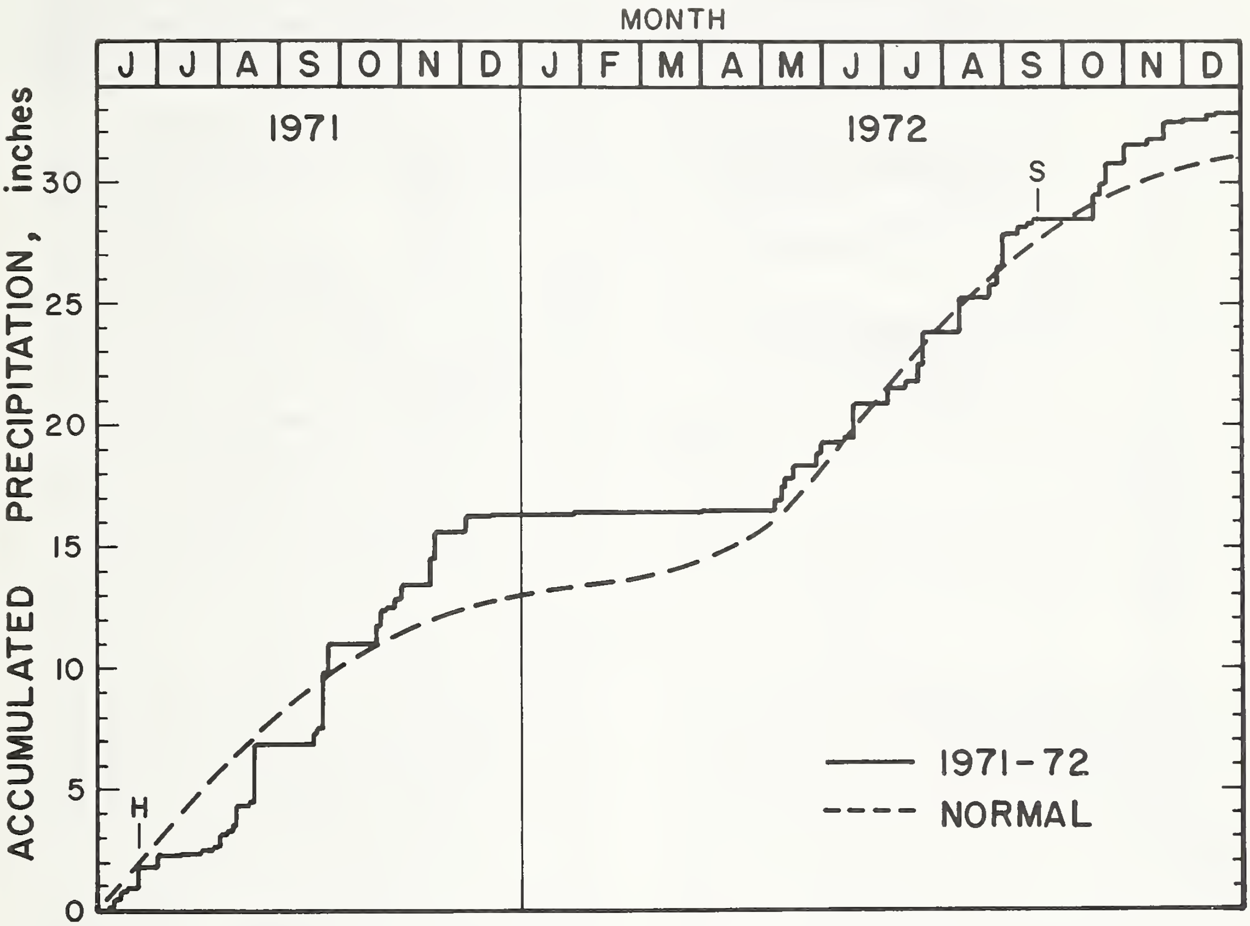

FIGURE 19.—Normal and actual accumulated precipitation, 1971-72.

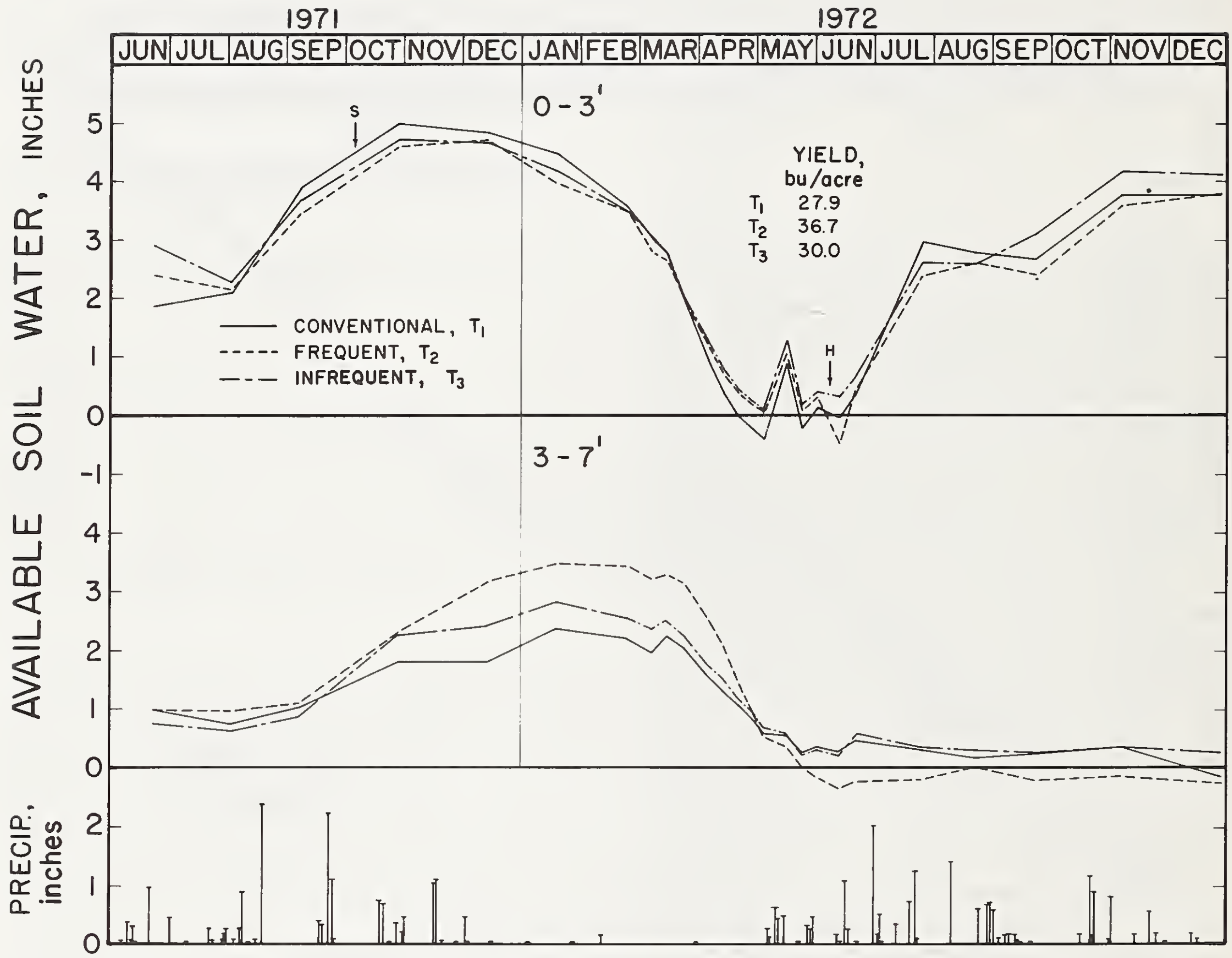

Figure 20.—Average available soil water and average crop yield by tillage treatment, block I (in wheat), 1971-72.

treatment ranked in the same order as the amount of available water in the 3- to 7-foot soil zone during the winter (fig. 20).

The reason for the pronounced visual signs of water stress that were shown by the crop in the spring of 1972 can be readily seen in figure 21. By May 1 the minimum point of exhaustion had already been reached throughout a 5-foot soil depth. The excellent root system of this crop was still functioning, however, as can be seen by the speed with which water from the rains in early May was extracted from the top foot of soil. This behavior differed greatly from that of the 1971 crop (fig. 18).

Grain yields of individual plots in 1972 were more variable than usual because of the effects of a late freeze in May and drought. As often occurs during a severe drought, the crop showed contrasting green and burned areas that corresponded to differences in soil properties beneath the crop. The plots were dried out more thoroughly in 1972 than in any other year of the study (figs. 44 and 45). The total stored soil water used, 6.93 inches, was matched only by the 1975 crop and is probably near the maximum possible for this soil.

Block II, in fallow.—The 1971-72 fallowing period started out with an average total of 2.91 inches of available water in the 7-foot soil profile, which was left over from the short, low-yielding 1971 crop. Good soil water gains were made during the last 4 months of 1971 as a result of much-above-normal precipitation (figs. 19 and 22). Very dry conditions prevailed during the first 4 months of 1972. Although water in the top 3 feet of soil decreased during this period, gradual gains continued to be made in the 3- to 7-foot soil zone. Precipitation from May 1 to the end of 1972 was above normal (fig. 19), but water gained during this period was slight because of heavy weed growth and cultivation (fig. 22). The T_1 and T_2 treatments received five and seven plowings, respectively, in 1972. Although not much additional gain in total available soil water occurred from July to the end of the year, frequent rains during the latter part of August and the early part of September served to get the plow layer in a near-ideal condition for seeding wheat.

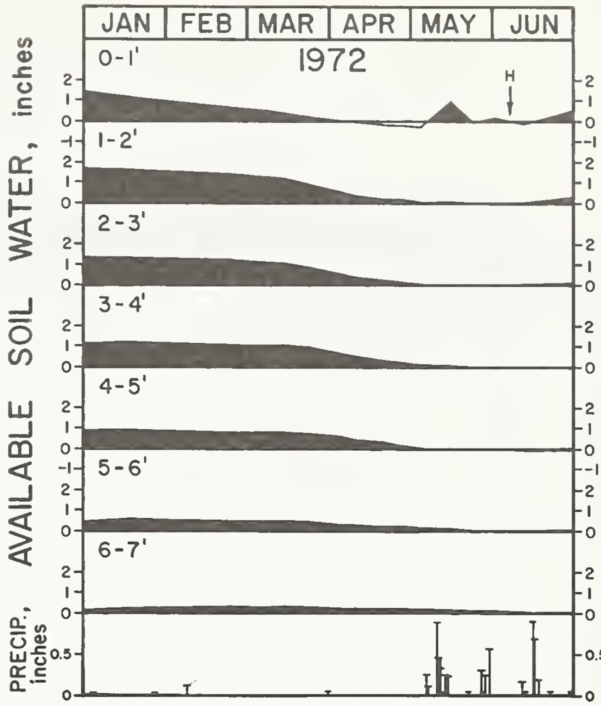

Figure 21.—Average available soil water by 1-foot-depth increments, block I (in wheat), 1972.

1972-73

Block I, in fallow.—Because of efficient water extraction by the 1972 wheat crop, the block I test plots started the 1972-73 fallowing season with practically no available water left in the soil profile. However, from wheat harvest to the end of 1972 precipitation was above normal, causing soil water gains averaging about 4 inches in the zero- to 3-foot zone (figs. 23 and 24). Precipitation in October and November, which included a total of 10 inches of snow from four storms, was very effective in adding to the soil water. Large gains in water below 3 feet first occurred after heavy precipitation in March 1973 (fig. 24). By mid-August 1973, the average total available water in 7 feet of soil had reached the unusually high level of 8.45 inches. During the 1972-73 fallowing season, a total of 30 inches of snow was received from nine separate storms, compared to a normal of 13 inches; thus, precipitation during the winter months was much above normal. The total available water at the end of the fallowing period averaged 7.87 inches, the most that occurred during this experiment (figs. 44 and 45). The higher average water content of the T_3 treatment, which persisted in the 3- to 7-foot soil zone through the summer of 1973 until seeding, was due to extra water that was trapped in the form of

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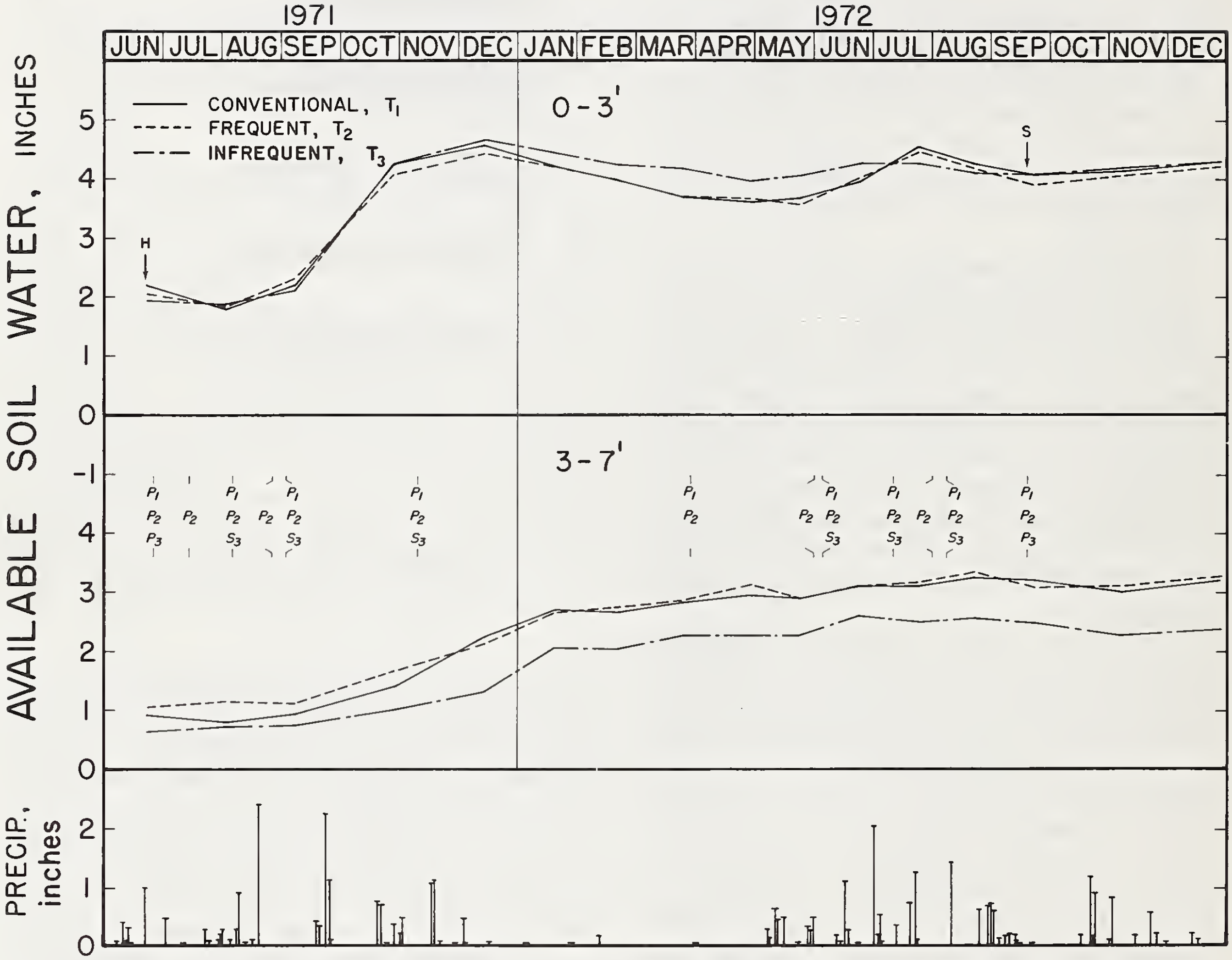

Figure 22.—Average available soil water and plowing and spraying dates by tillage treatment, block II (in fallow), 1971-72.

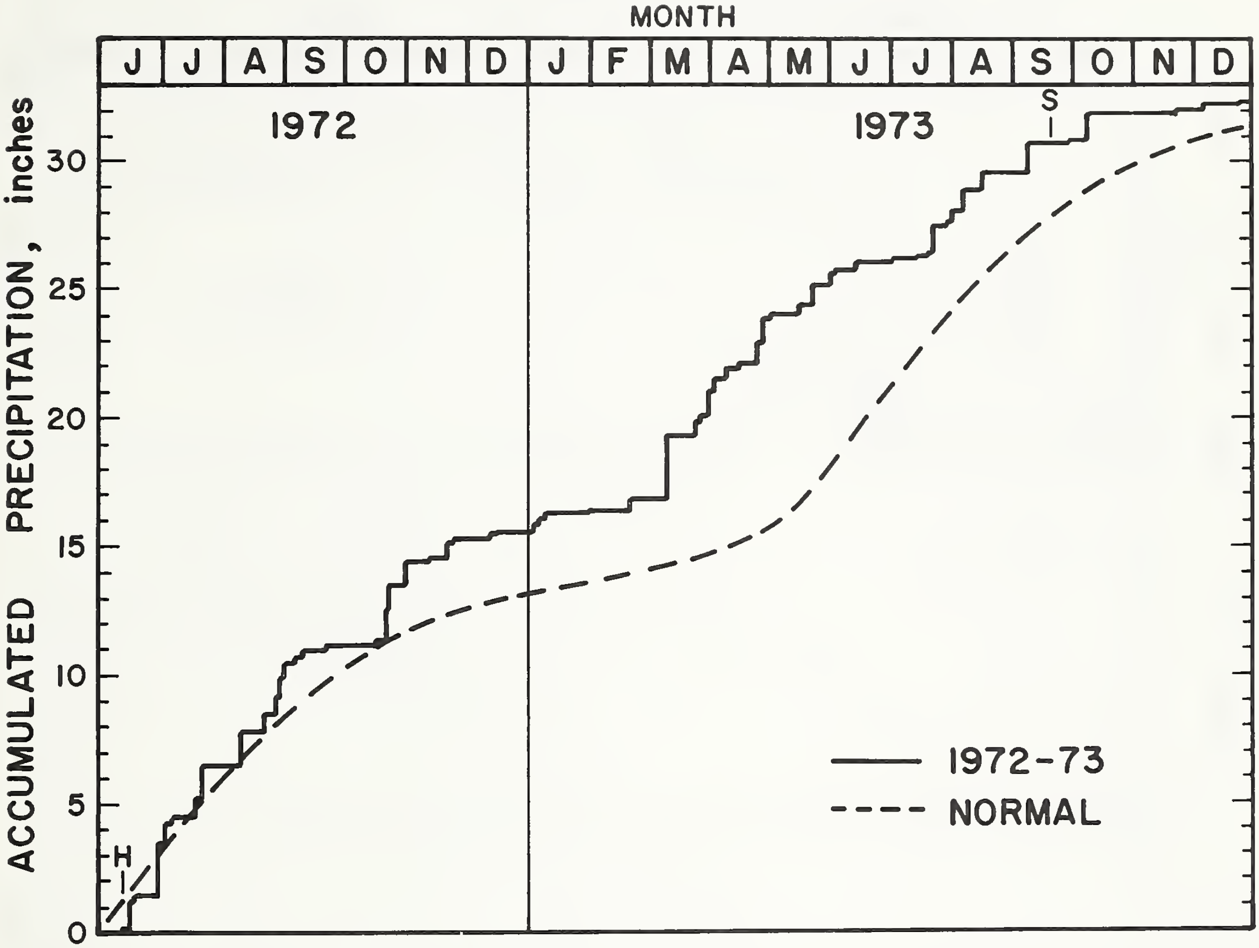

FIGURE 23.—Normal and actual accumulated precipitation, 1972-73.

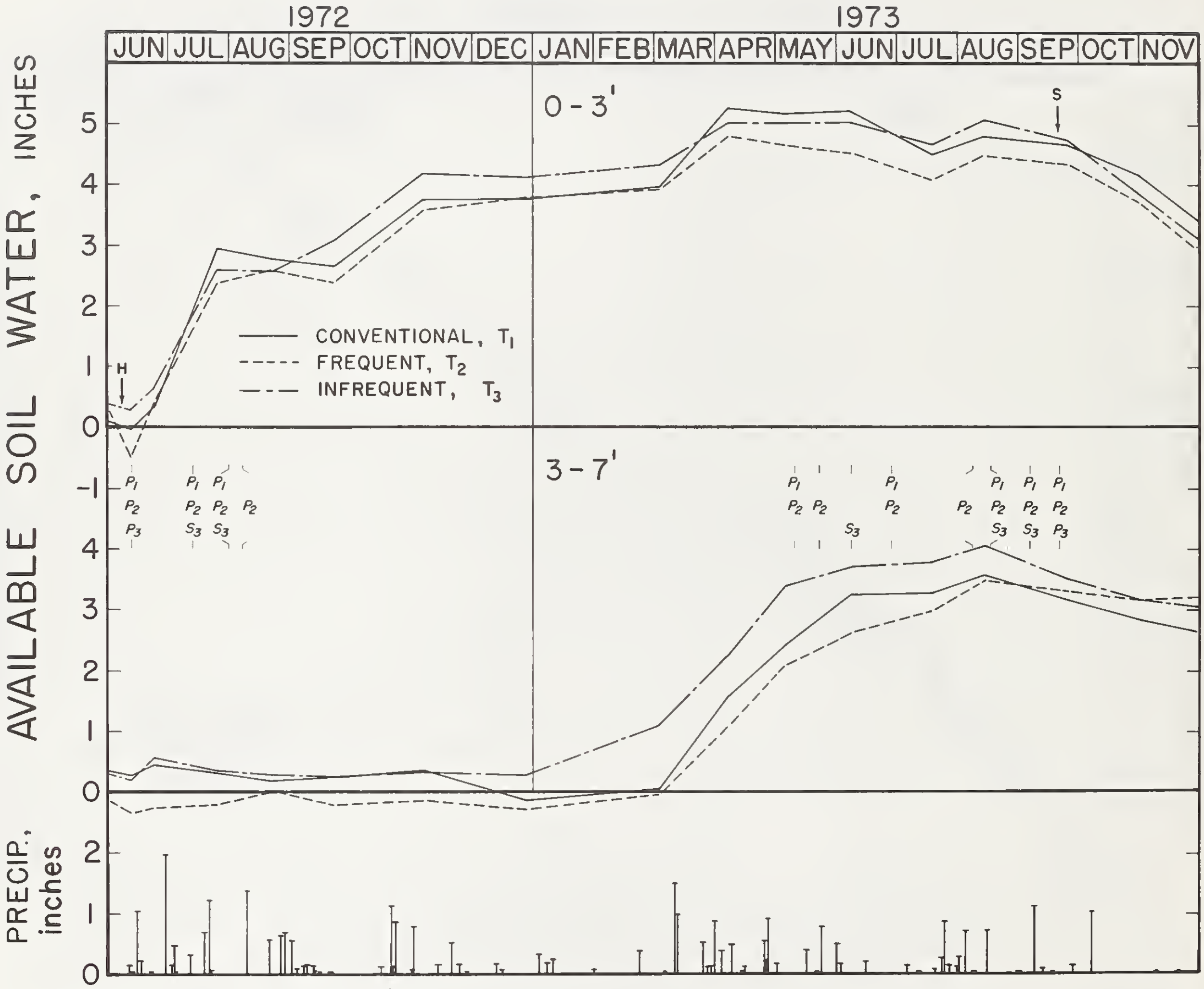

Figure 24.—Average available soil water and plowing and spraying dates by tillage treatment, block I (in fallow), 1972-73.

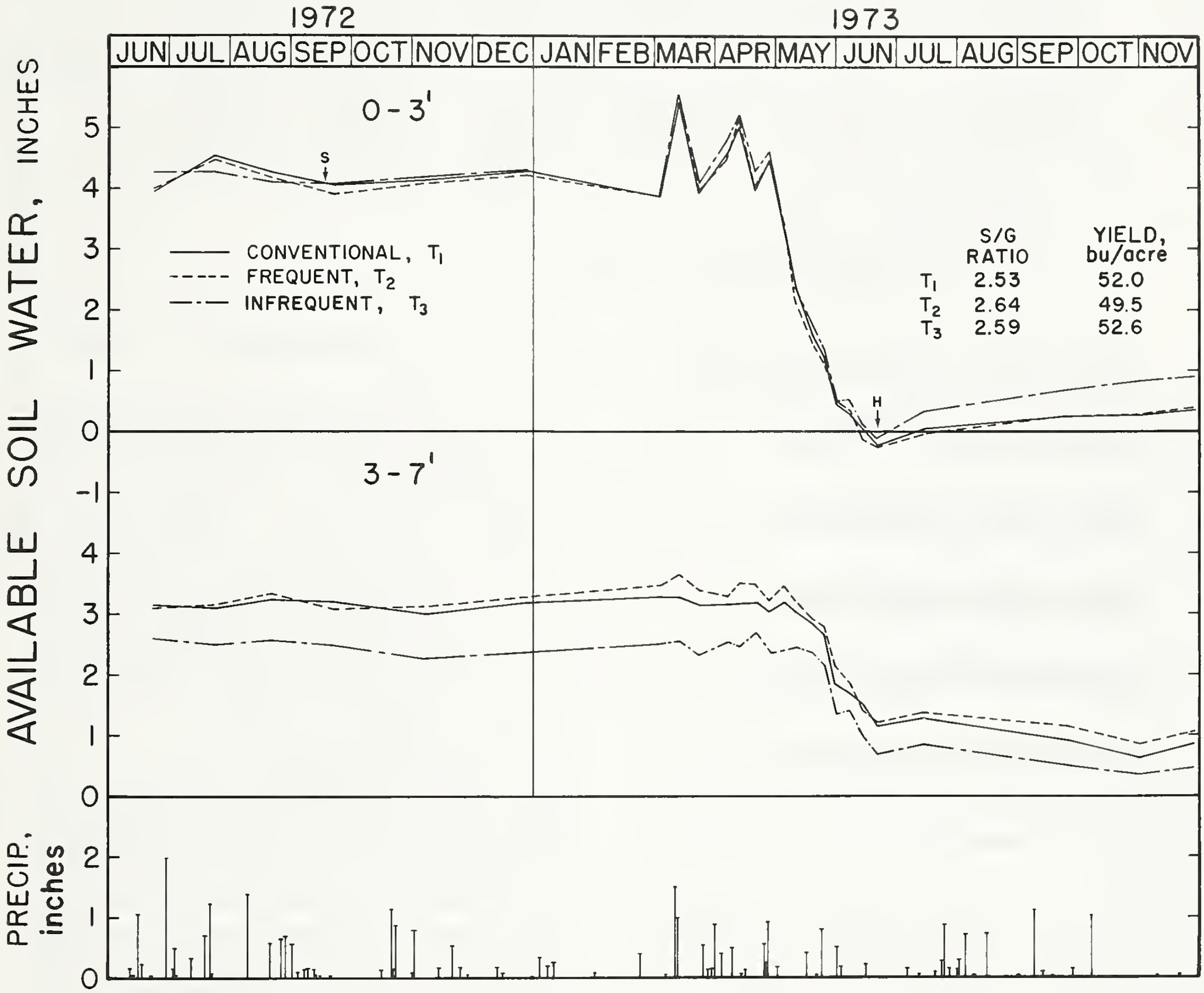

Figure 25.—Average available soil water, straw-grain (S/G) ratio, and average crop yield by tillage treatment, block II (in wheat), 1972-73.

Table 2.—Average yield and straw-grain ratio for individual crop years and the associated average amount of soil water used, growing season precipitation, and total amount of water used

Measurement	Year of harvest							
	1970	1971	1972	1973	1974	1975	1976	1977
Yield ....bu/acre ...	27.3	10.5	31.5	51.4	12.4	37.0	15.6	13.7
S/G ratio[1] ....lb/lb ...	2.53	1.57	1.75	2.59	2.87	1.70	1.97	1.49
Soil water[2]..........inches ...	5.70	1.58	6.93	6.12	3.85	6.97	2.11	- 0.03
Precipitation[3] ....do.....	8.80	2.51	8.32	15.76	9.53	10.26	7.48	9.03
Total water ....do.....	14.5	4.1	15.3	21.9	13.4	17.2	9.6	9.0

[1] Straw-grain ratio.
[2] Water used from seeding to harvest.
[3] Precipitation received from seeding to harvest.

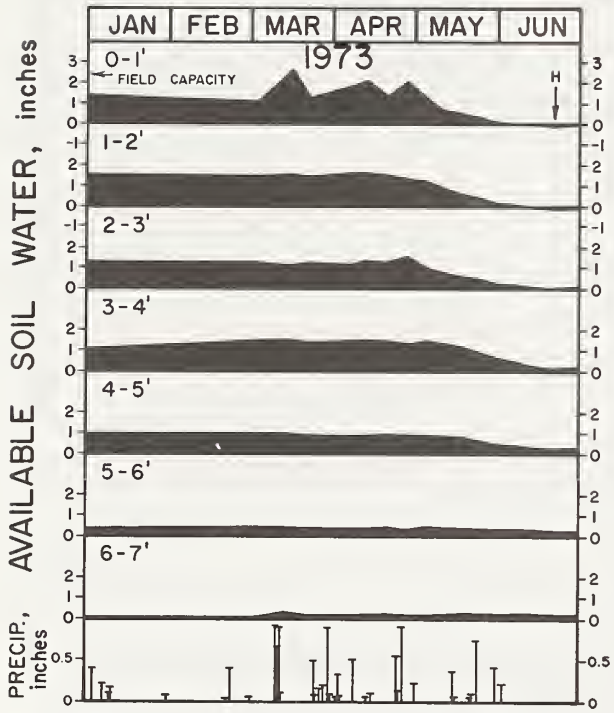

Figure 26.—Average available soil water by 1-foot-depth increments, block II (in wheat), 1973.

snow by the more erect stubble of this treatment (fig. 24).

Block II, in wheat.—The 1973 wheat crop set a 35-year record at the Research Center at Bushland (fig. 4). Seeding conditions in 1972 were ideal, with an average of 6.92 inches of available water in the soil (figs. 25 and 45). Rains in October totaling 2.25 inches, which enabled the crop to become well established, were followed by an unusually large number of sleet and snow storms in November and December. Precipitation from seeding until the end of May 1973 was 1.6 times normal. Heavy precipitation in March, coming at a time of cool temperature and low evaporation rate, caused the topsoil of the wheat plots to become water-saturated. In fact, the soil was so wet that in making neutron meter readings it was difficult to move the rolling platform from one block of test plots to the other in the deep mud. Had it not been for the curbs and rolling platform, it would have been impossible to obtain soil water information about this historic 1973 crop. Soil water readings were made on a total of 18 dates between seeding and harvest without harm to the crop or soil. Because the wheat attained the unusual height of 45 inches, it was necessary to install extra-long extensions on the rolling platform (fig. 7).

Because of the abundance of water and cooler-than-average maximum temperatures during the first part of 1973, the wheat crop in early spring was about 10 days later than normal and produced an unusually large amount of foliage. The heavy vegetation resulted in a very high evapotranspiration rate as temperatures rose later in the spring. The evapotranspiration rate at its peak in May was 0.3 inch per day, approximately the same as the peak-period rate of irrigated wheat,

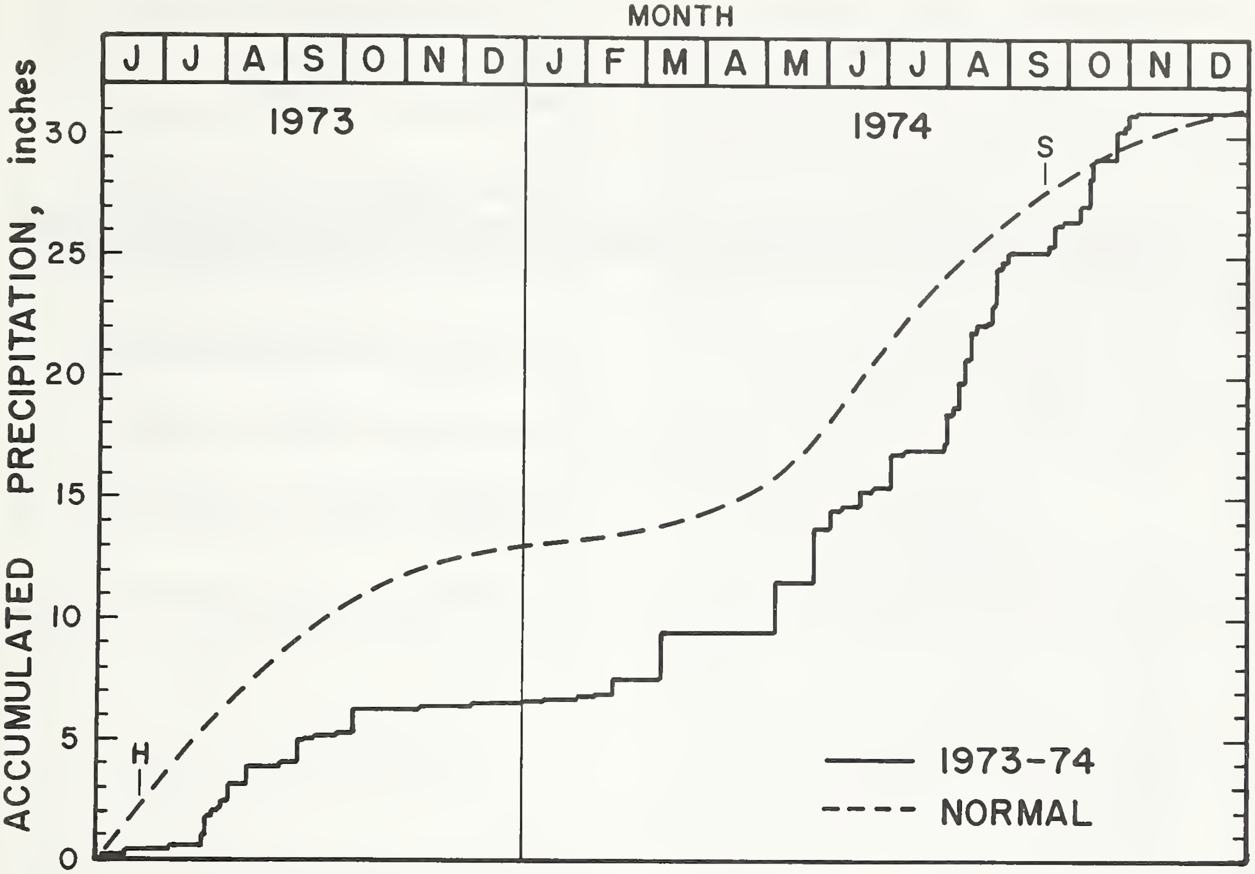

FIGURE 27.—Normal and actual accumulated precipitation, 1973-74.

grain sorghum, and cotton. The deficient June rainfall of 0.39 inch (compared to a normal of 3.16 inches) combined with hot weather to cause the crop to ripen rapidly and mature about 5 days earlier than normal despite its lateness earlier in the spring. Although the yield potential would have been greater had the normal amount of rain fallen in June and given the crop time to fully utilize the subsoil water, the probability of loss from hail and wind would also have been greater. Losses from these factors in 1973 were negligible, and harvesting conditions were ideal. This resulted in dryland wheat yields that were probably near the realizable maximum for this area. The 1973 wheat crop produced 2.6 times the long-time average yield of grain and 4 times the long-time average yield of straw for wheat grown on fallowed land at the Research Center. For all tillage treatments, the average grain yield was 51.4 bushels per acre, and the average straw yield was 8,000 pounds per acre. Total water use (soil water plus precipitation) by this crop averaged 21.9 inches, more than 5 times the amount used by the 1971 crop and the largest total water use by any crop in this study (table 2).

Figure 26 shows the average-available-water profiles for the 1-foot soil layers of the wheat plots from January to June 1973. In mid-March the water content was above field capacity in the top foot of soil and approached field capacity on two later sampling dates in April. In the 1- to 2-foot, 2- to 3-foot, and 3- to 4-foot soil zones, a gradual increase in soil water occurred which, depending on depth in the soil, continued from mid-April to early May. After that, a rapid decrease in soil water occurred, which extended to a soil depth of about 5 feet.

1973-74

Block I, in wheat.—The 1974 crop is of special interest since it came after a memorable summer-fallowing period during which there was a large amount of winter precipitation (fig. 23). It had the

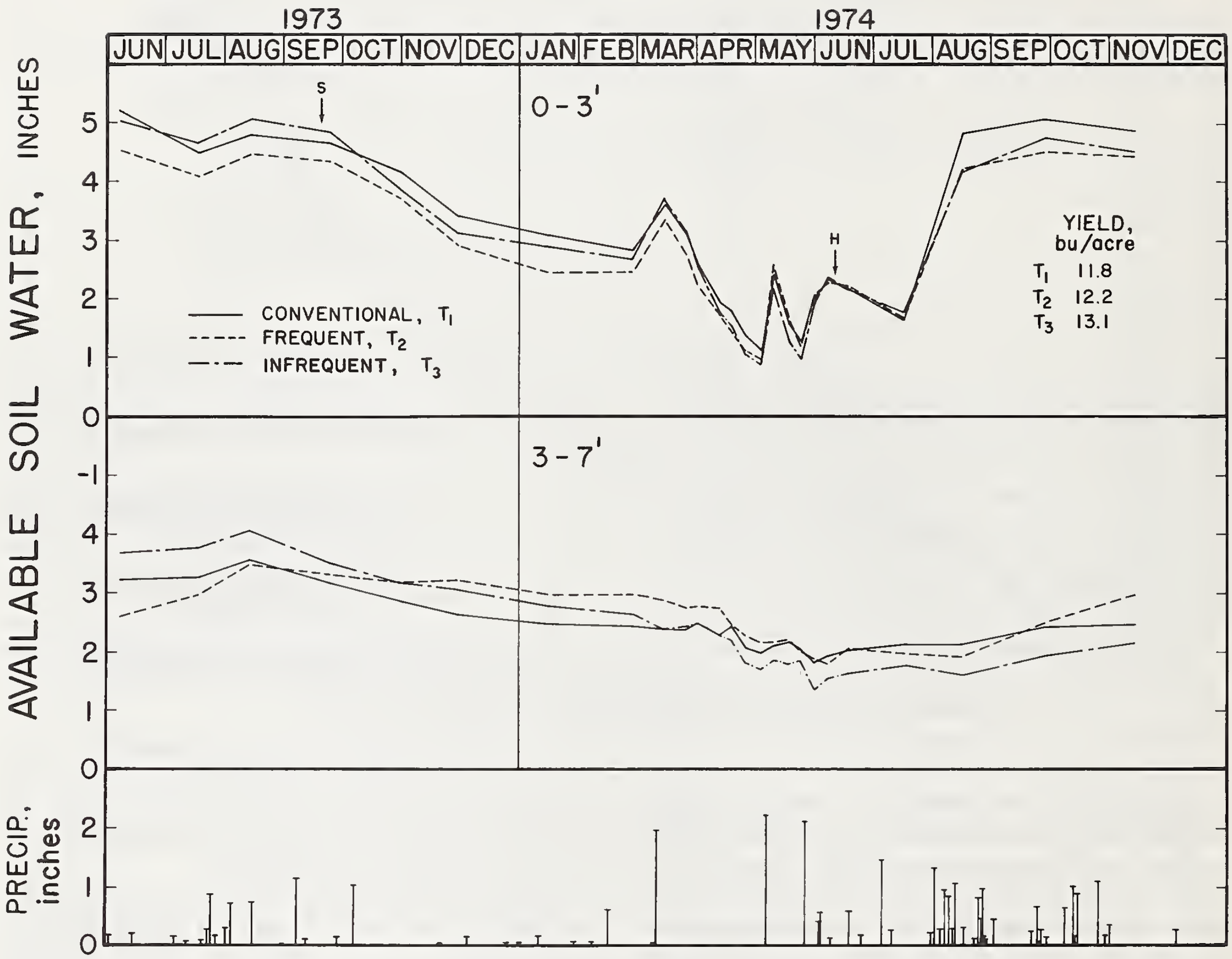

FIGURE 28.—Average available soil water and average crop yield by tillage treatment, block I (in wheat), 1973-74.

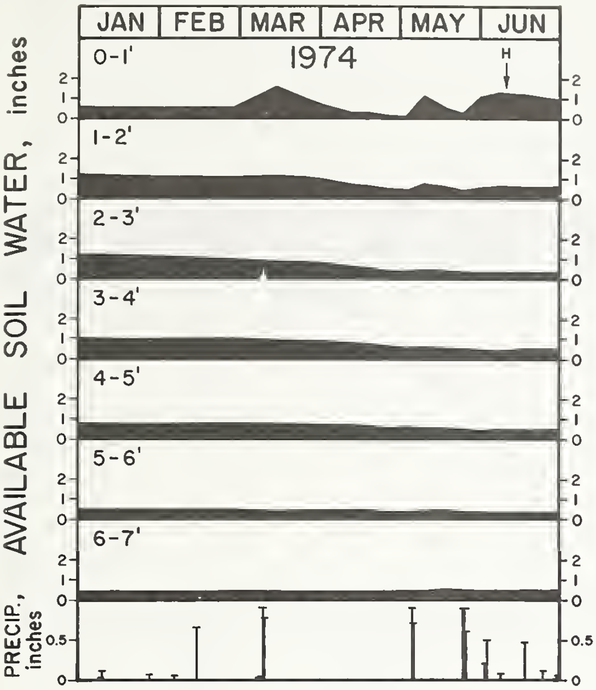

FIGURE 29.—Average available soil water by 1-foot-depth increments, block I (in wheat), 1974.

most total available soil water at seeding of any crop in this study, 7.87 inches in 7 feet of soil (fig. 44). The crop was a disappointment in that it fell short of expectations based on available water at seeding but exceeded expectations based on its appearance near harvest. The crop was seeded on September 19 and was rather slow to emerge. A rain of 1.05 inches occurred on October 6, but it apparently came too soon after seeding to benefit the development of the secondary roots and did not contribute much to the general vitality of the crop (fig. 27). This was the only precipitation that occurred during the last 3 months of 1973. During the first 5 months of the crop season, soil water depletion was unusually rapid (fig. 28). This was probably caused by abnormally high temperatures in October and November. The 5-month period from October to March was the driest on record for the Texas Panhandle as a whole. These circumstances left the crop in a weakened condition from which it was not able to fully recover despite a heavy rain of 2 inches in March. Most farmers' fields of continuous wheat were too poor to harvest in 1974, and the average yield of wheat grown on summer-fallowed land was but 5 bushels per acre. The low yields were largely a result of water depletion caused by excessive disking to reduce the amount of straw from the previous crop and to control weeds. Wheat on the plots of this experiment was somewhat better than that on most farmers' fields, but it received hail damage on May 5 and 25 that caused an estimated yield reduction of over 50 percent. The net result was that the crop yielded an average of only 12.4 bushels per acre and left a total of 4 inches of available soil water (fig. 44). By comparison, the very efficient 1972 crop yielded 2.5 times as much as the 1974 crop and left no available water in the soil at harvest. Total water use (soil water extracted plus precipitation) did not differ greatly for the 1972 and 1974 crops, being 15.3 and 13.4 inches, respectively (table 2). The 1974 crop received more precipitation than the 1972 crop but used much less soil water.

Water from the 2-inch rainstorm on March 10, 1974, hardly penetrated below the top foot of soil and was largely depleted by the time additional heavy precipitation occurred in early May (fig. 29). Soil water from the early May rains was rapidly extracted by the crop, but water from rains in late May and June that accumulated in the top foot of soil was not of much benefit to the crop. The high straw-grain ratio of the 1974 crop (2.87) is no doubt partly attributable to hail damage.

Block II, in fallow.—Because of dry weather, there was no net gain in stored water during the first 9 months of the fallowing period (fig. 30). There was a slight gain in soil water in the zero- to 3-foot zone but a slight loss in the 3- to 7-foot zone. However, a 2-inch rain on March 10, 1974, resulted in a large increase in soil water in the zero- to 3-foot zone. No additional precipitation was received until May, during which two rains totaling 4.30 inches caused additional soil water gains in this zone. August rains totaling 7.49 inches further increased the soil water in the zero- to 3-foot zone and caused some increases in the 3- to 7-foot zone. By seeding time in September, the average total available water in the block II test plots was 7.23 inches (fig. 45). Five inches of this amount were in the top 3 feet of soil. Frequent showers in the wet fall of 1974 provided a number of opportunities for seeding wheat, unlike in most years when there may be only a brief period of a few days when a crop can be seeded and a stand obtained. The showers caused growth of an abundance of heavily rooted volunteer wheat that was difficult to kill by plowing.

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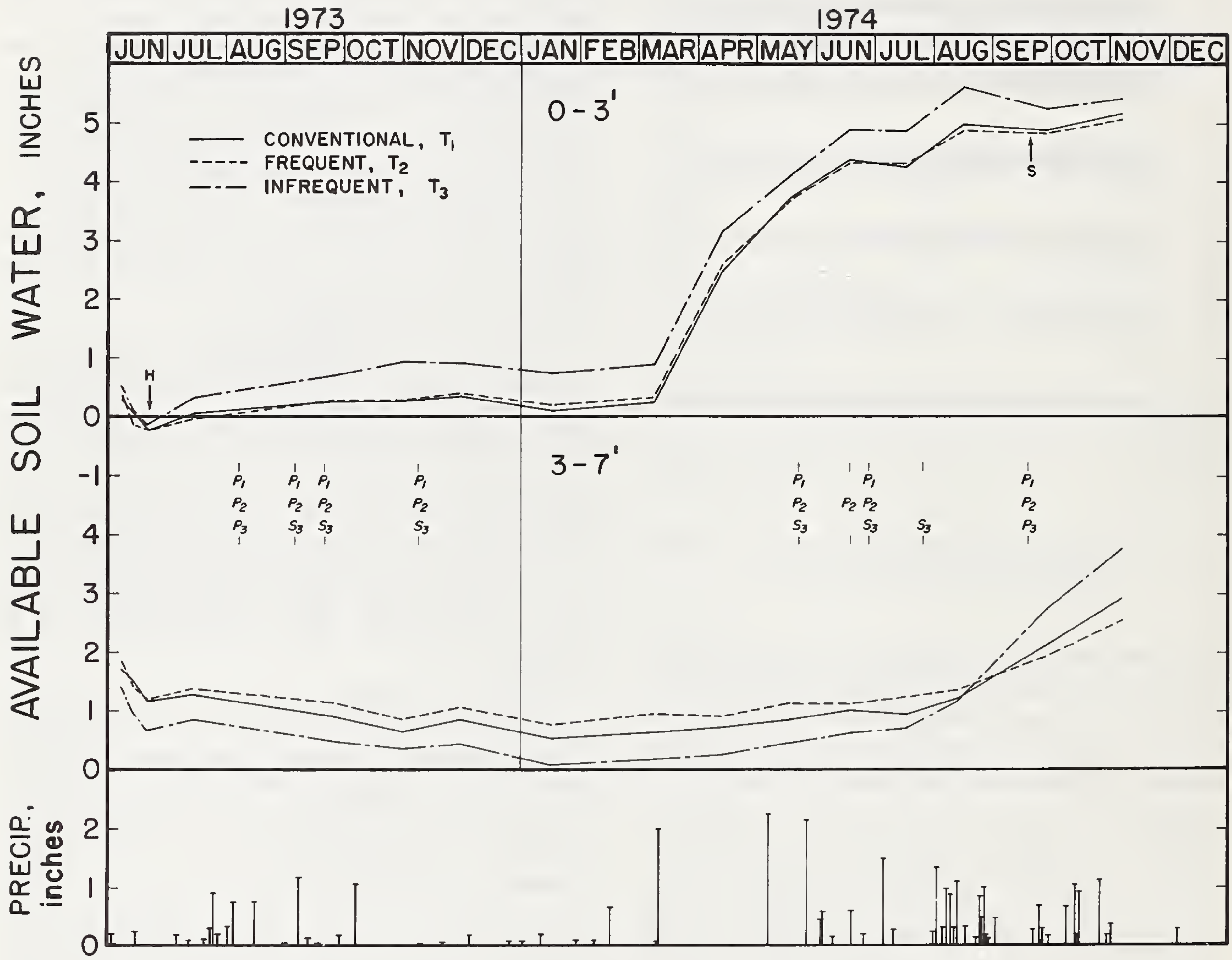

Figure 30.—Average available soil water and plowing and spraying dates by tillage treatment, block II (in fallow), 1973-74.

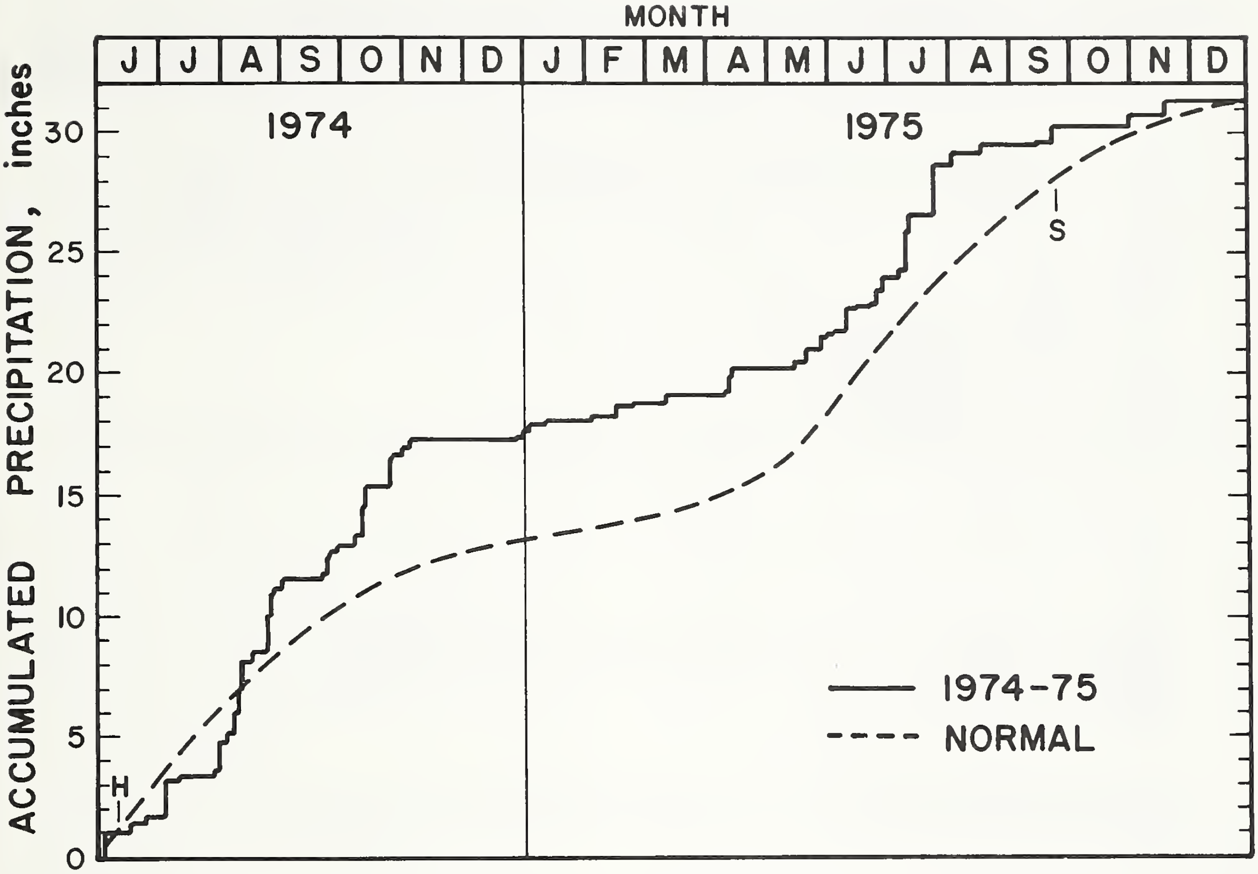

FIGURE 31.—Normal and actual accumulated precipitation, 1974-75.

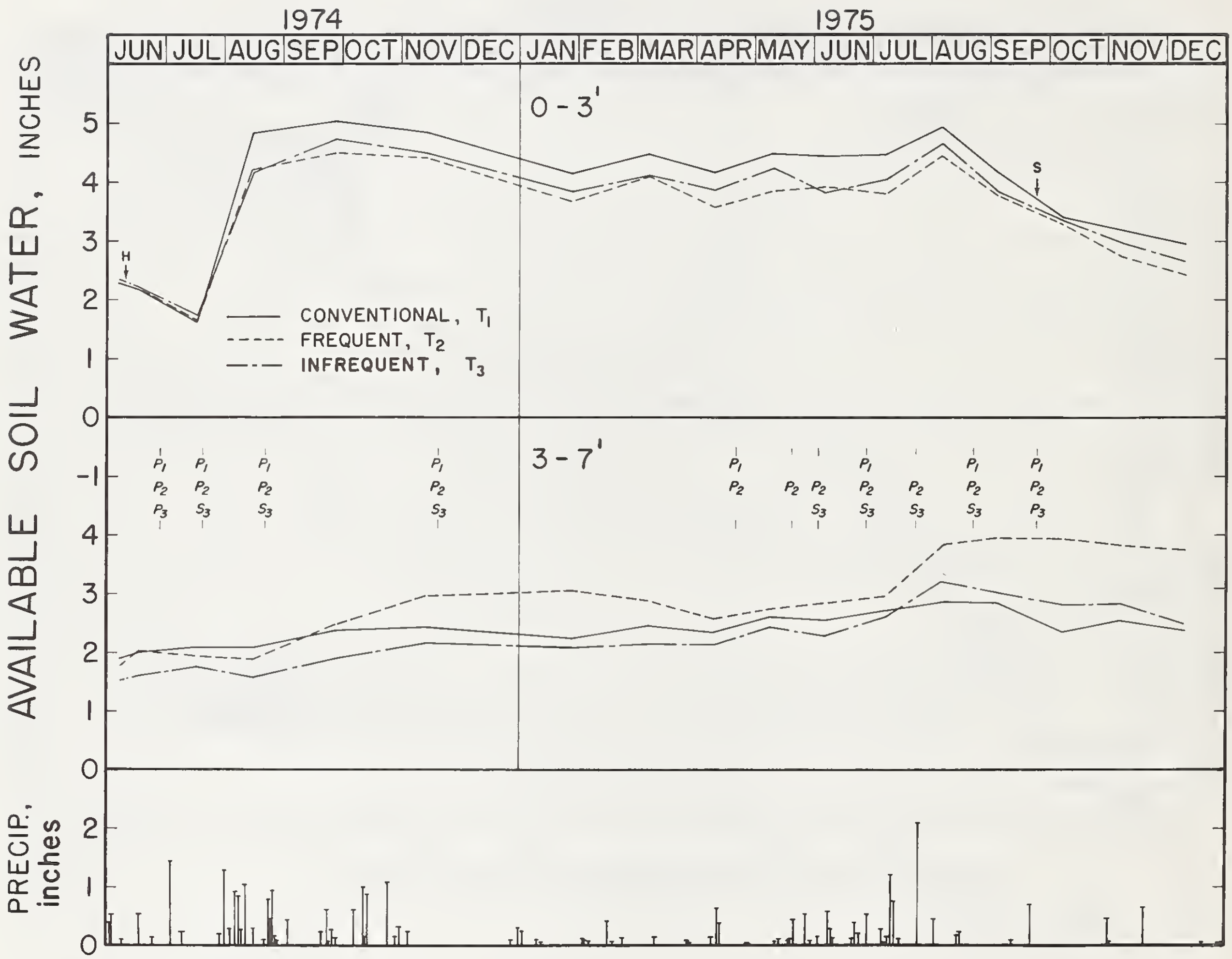

FIGURE 32.—Average available soil water and plowing and spraying dates by tillage treatment, block I (in fallow), 1974-75.

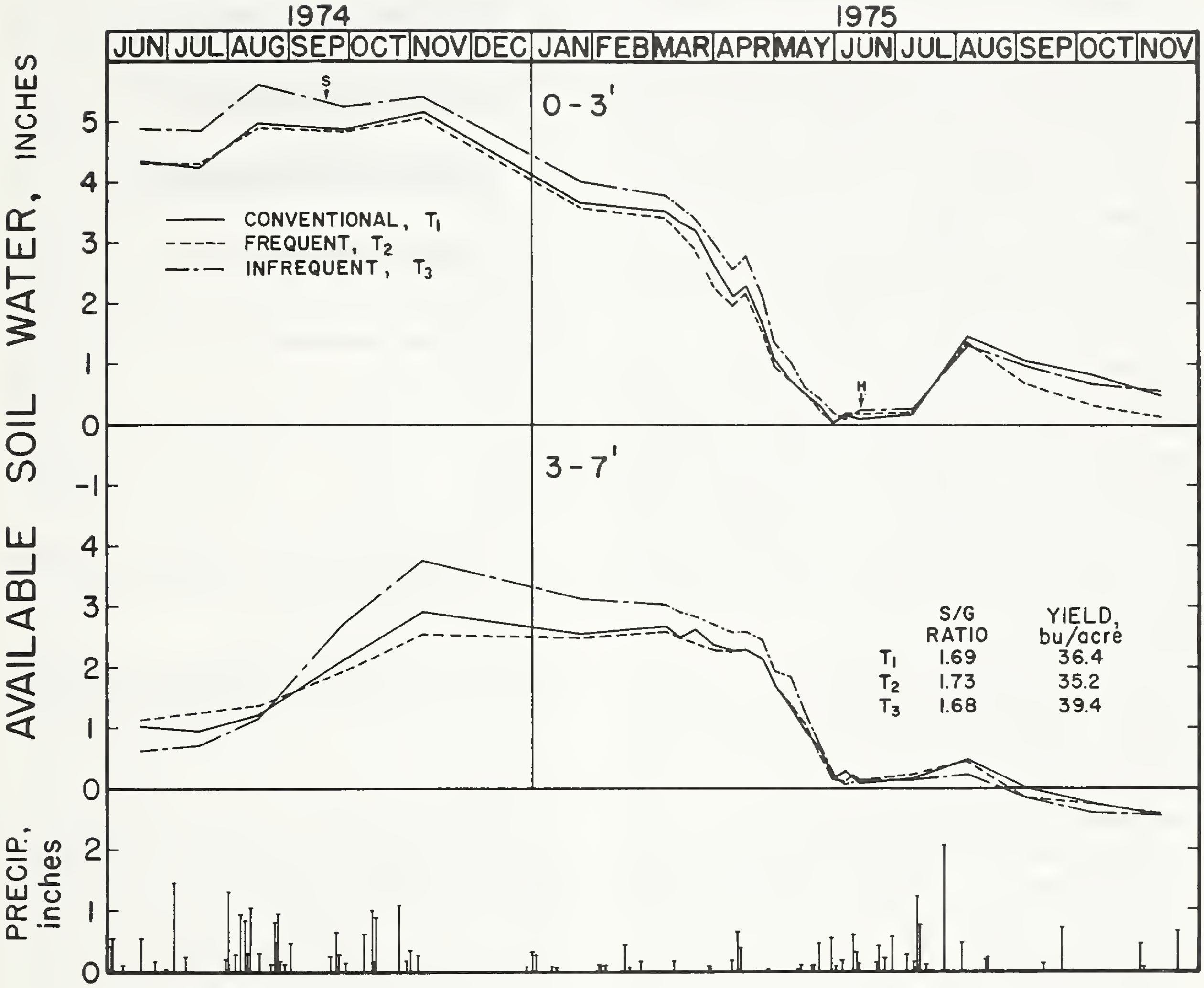

FIGURE 33.—Average available soil water, straw-grain (S/G) ratio, and average crop yield by tillage treatment, block II (in wheat), 1974-75.

1974-75

Block I, in fallow.—The 1974-75 summer-fallowing period began with 4.02 inches of available water already in the soil because of poor utilization by the 1974 crop (fig. 44). Periods of high rainfall occurred from August through October 1974 and in July 1975 (fig. 31). The most striking gain in soil water was in August 1974 (fig. 32). Although total available water was quite high at seeding in the fall of 1975 (6.36 inches in 7 feet of soil), the surface soil was very dry because of deficient rainfall during August and September. Only one brief opportunity occurred for getting a stand of wheat during the fall of 1975, when a 0.70-inch rain fell on September 20.

Block II, in wheat.—The 1975 crop was noteworthy because of the thoroughness with which it removed stored water from the soil (fig. 33). It produced an excellent yield, averaging 37 bushels per acre despite a long drought that extended from the beginning of November to mid-May. The previous record for extraction of stored soil water in this study was 6.93 inches by the 1972 crop. This record was equalled by the 1975 crop, which used 6.97 inches of soil water (fig. 45 and table 2).

This crop was seeded when there was a good supply of available soil water, 7.23 inches, of which 5 inches were in the top 3 feet of soil. Above-normal rainfall in September and October 1974 enabled exceptionally strong root development by the newly seeded wheat. In fact, volunteer wheat was difficult to kill in the fall of 1974. However, dry weather that prevailed after growth resumed in the spring caused the plants to be short in stature and continually in need of water. The high average yield of 37.0 bushels per acre was greater than preharvest predictions. The straw-grain ratio of 1.7, which was low considering the relatively high yield, was due to dry weather in the spring. The small amount of foliage produced, together with an excellent root system, made the 1975 crop an efficient water-user. As in 1972, little or no available water was left in the soil at harvest (fig. 45).

The available-water profiles of 1-foot soil layers (fig. 34) are convex upward, indicating that soil water was being extracted at an accelerated rate until it was almost completely exhausted. As in 1972, water from rains in May and June appeared to be rapidly used in evapotranspiration, so the effect on the soil water content was brief.

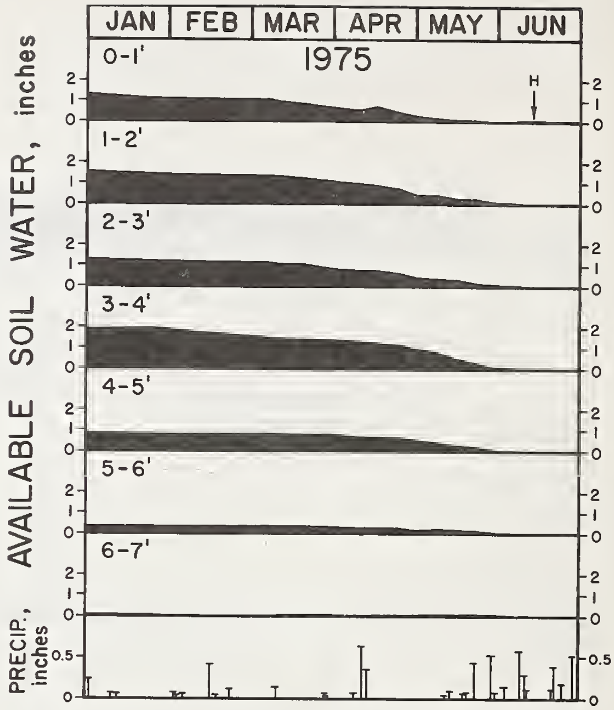

Figure 34.—Average available soil water by 1-foot-depth increments, block II (in wheat), 1975.

The 1975 crop differed markedly from the 1971 and 1974 crops in this regard (figs. 18 and 29).

1975-76

Block I, in wheat.—Because of dry soil and deficient rainfall, the only opportunity for seeding wheat in the fall of 1975 was a brief period after a shower of 0.70 inch on September 22. Only a moderately good stand was obtained and, owing to a long dry spell that lasted until late April 1976, the crop made little growth (figs. 35 and 36). There was very little available water in the top foot of soil at any time from January to June 1976 (fig. 37). The average yield was 15.6 bushels per acre. The 1976 crop used only 2.11 inches of stored soil water (fig. 44). The outstanding 1972 crop had 0.51 inch more available soil water at seeding than did the 1976 crop and received 0.84 inch more precipitation during the growing period (table 2). The big difference in the two crop seasons was the amount of fall rainfall, which was sufficient for good root development and tillering of the crop in 1971 but not in 1975. The 1972 crop used 6.93 inches of soil water and the 1976 crop 2.11 inches (table 2). The high water level in the 3- to 7-foot

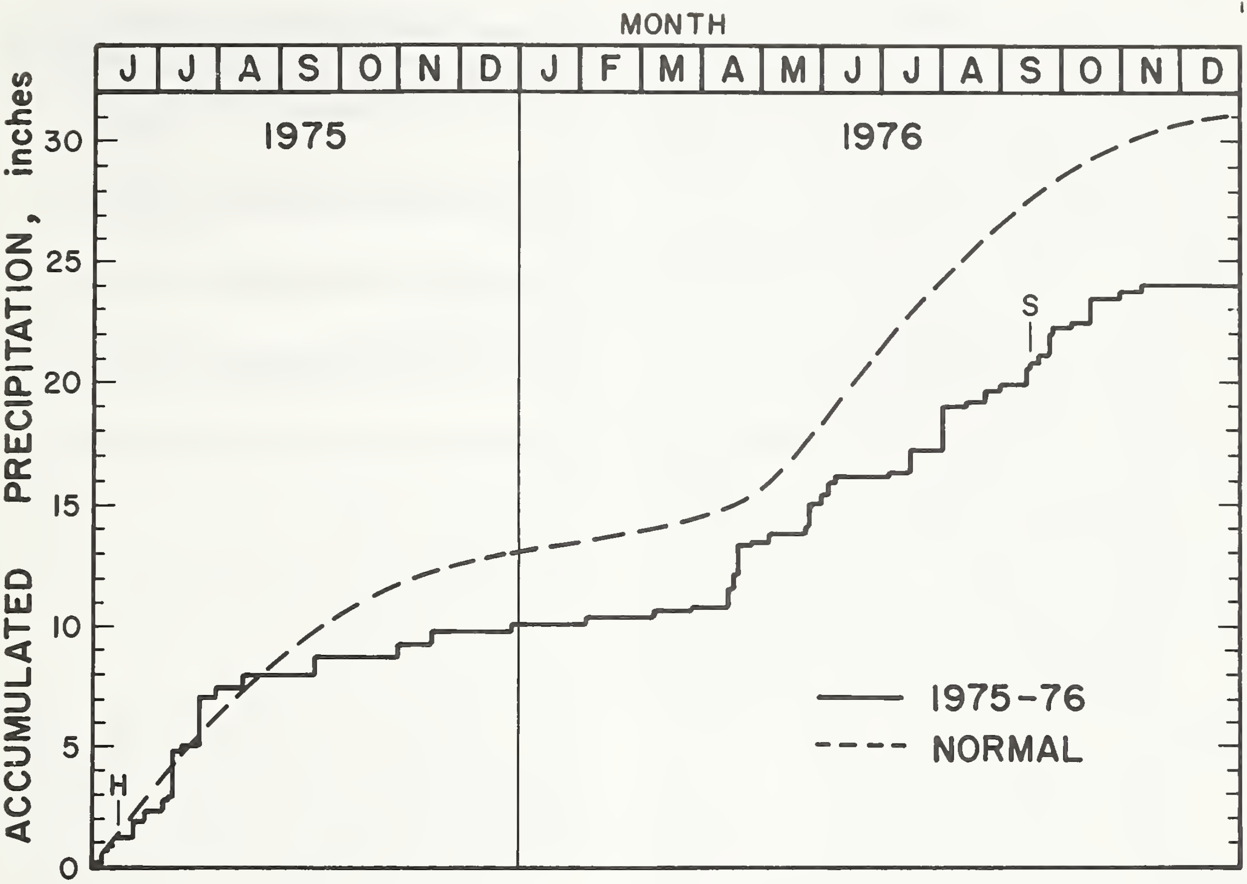

FIGURE 35.—Normal and actual accumulated precipitation, 1975-76.

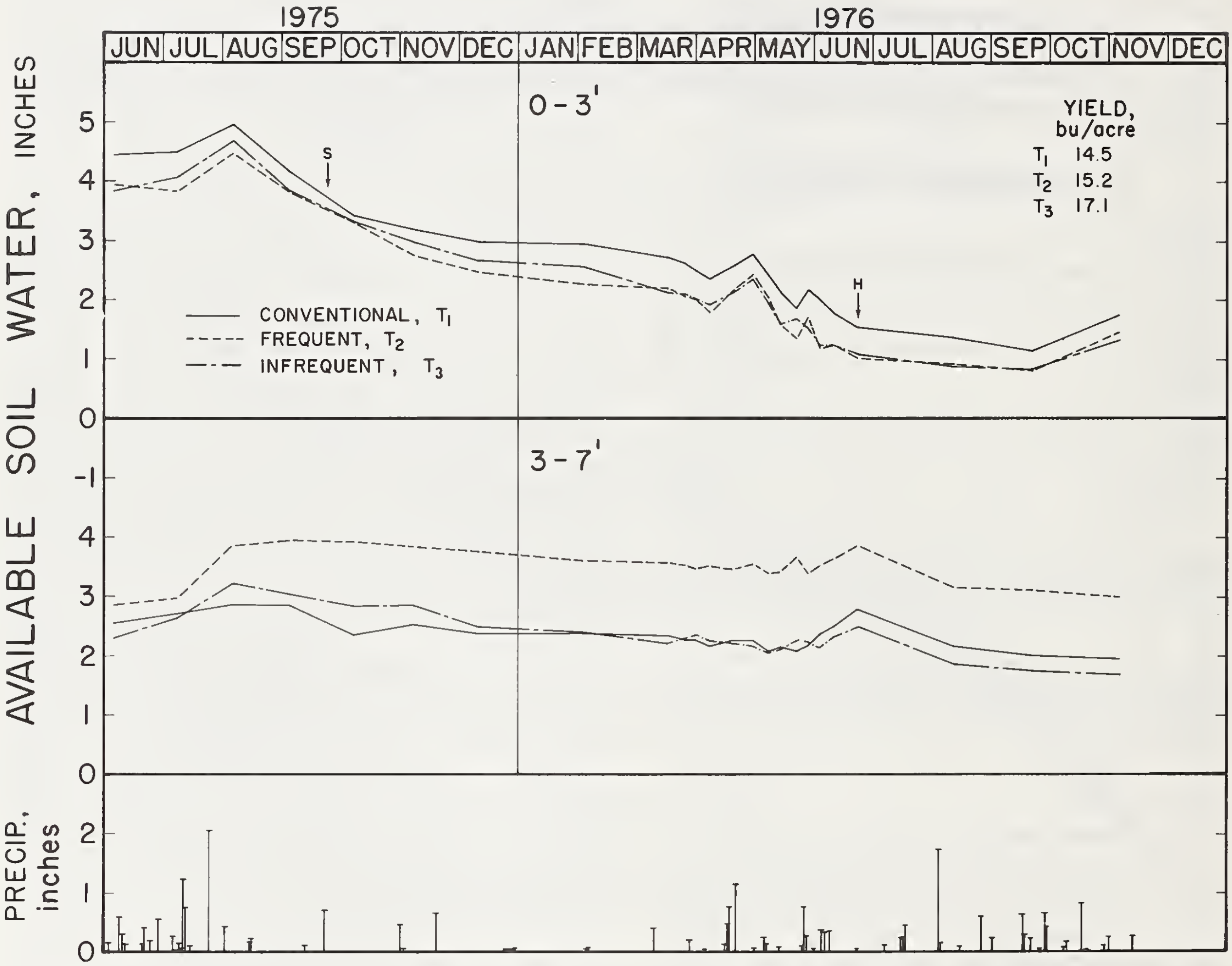

FIGURE 36.—Average available soil water and average crop yield by tillage treatment, block I (in wheat), 1975-76.

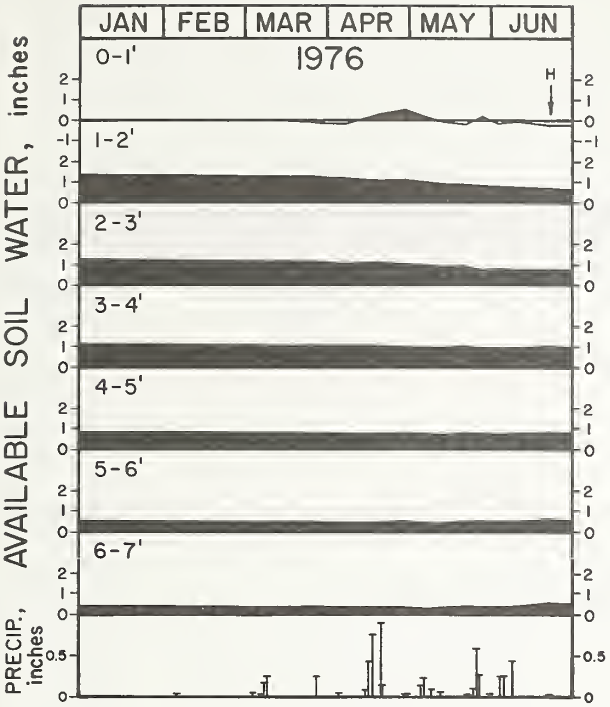

FIGURE 37.—Average available soil water by 1-foot-depth increments, block I (in wheat), 1976.

soil zone of the T_2 plots in 1975-76 dates back to a 2-inch rain on July 23, 1975 (fig. 36). The increased water intake on the T_2 plots was probably the result of plowing just before the rain (fig. 32). The zero- to 3-foot soil zone was nearly filled with water at that time, and no water was used by the 1976 crop from below this zone (fig. 37).

Block II, in fallow.—After being thoroughly dried out by the 1975 wheat crop, the block II test plots stored about 1.5 inches of soil water from showers in June and July 1975 (fig. 38). This stored water largely disappeared during the next 8 months because of dry weather, but gains were again made in April 1976. Rains during the rest of 1976 were below normal, and for the 1975-76 fallowing season as a whole precipitation was only three-fourths of normal. The amount of soil water available to the 1977 crop was the lowest of any crop in this study and totaled only 1.28 inches in the top 3 feet of soil. Because of water loss by direct evaporation, the soil water content below 4 feet was below the minimum point of exhaustion (fig. 45).

1976-77

Block I, in fallow.—For more than a year after the wheat harvest of June 1976, precipitation was much below normal and not much change in soil water content occurred (figs. 39 and 40). However, August 1977 was very wet, but weeds, cultivation, and hot weather wasted soil water and resulted in a dry surface soil at seeding. The last 4 months of 1977 were too dry to replenish the surface water, and the crop, which was seeded on September 29, 1977, did not come up. Some farmers cultivated their fallowed land around September 1, seeded immediately, and obtained adequate stands in some cases. As often happens with early planted wheat, however, the soil water was soon used up, and the wheat died before the dormant period. The higher water content in the 3- to 7-foot soil zone of the T_2 plots first occurred during a wet period in July 1975 and was still present more than 2 years later (fig. 40). The block I plots barely held their own with respect to water from harvest in 1976 to seeding in 1977. Water gained in the topsoil was offset by water lost in the subsoil. Failure to obtain a stand with the 1978 crop resulted in the decision to terminate this experiment in the spring of 1978, 10 years after it was begun.

Block II, in wheat.—The 1975-76 fallowing season did little to replenish the soil water that had been completely exhausted by the 1975 crop. Although a total of 2.55 inches of rain was received in September 1976, it came in the form of light showers on dry soil that were dissipated without being effective in adding to the soil water. As a result, water for seeding was meager in the fall of 1976, and the stand obtained was sparse. However, this was fortunate since the available soil water in the 7-foot profile totaled only 0.97 inch, which was inadequate to support a thicker stand. This was by far the smallest amount of stored water of any year in the study (figs. 44 and 45). No precipitation of importance occurred between mid-November 1976 and the last week of March 1977. In early May, as the critical heading stage of the crop approached, the average total available water in the top 3 feet of soil was only about 0.3 inch (fig. 41). The maximum total available water in the upper 3 feet of soil at any time from seeding until May 1, 1977, was only 1.5

(*Continued on page 40.*)

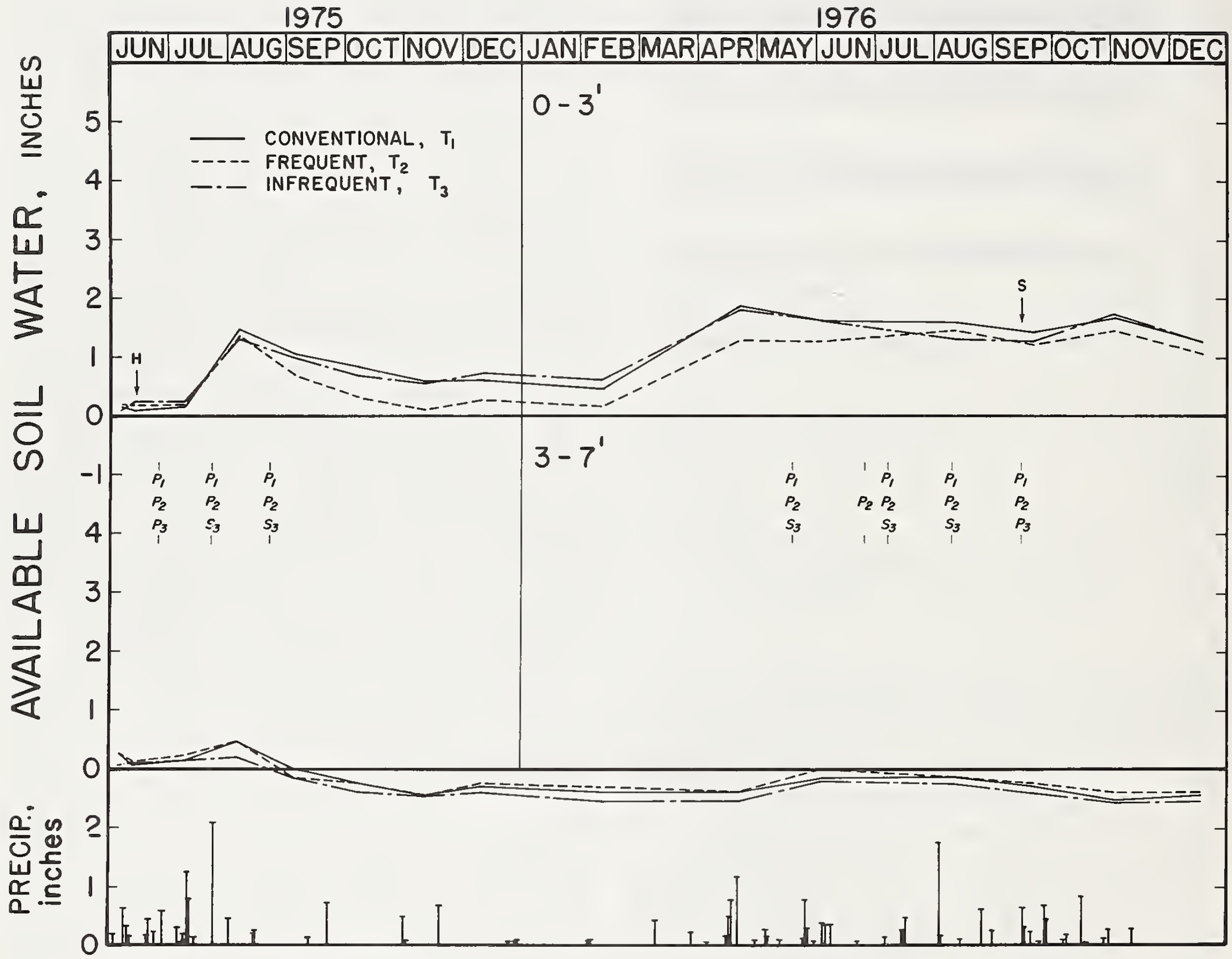

FIGURE 38.—Average available soil water and plowing and spraying dates by tillage treatment, block II (in fallow), 1975-76.

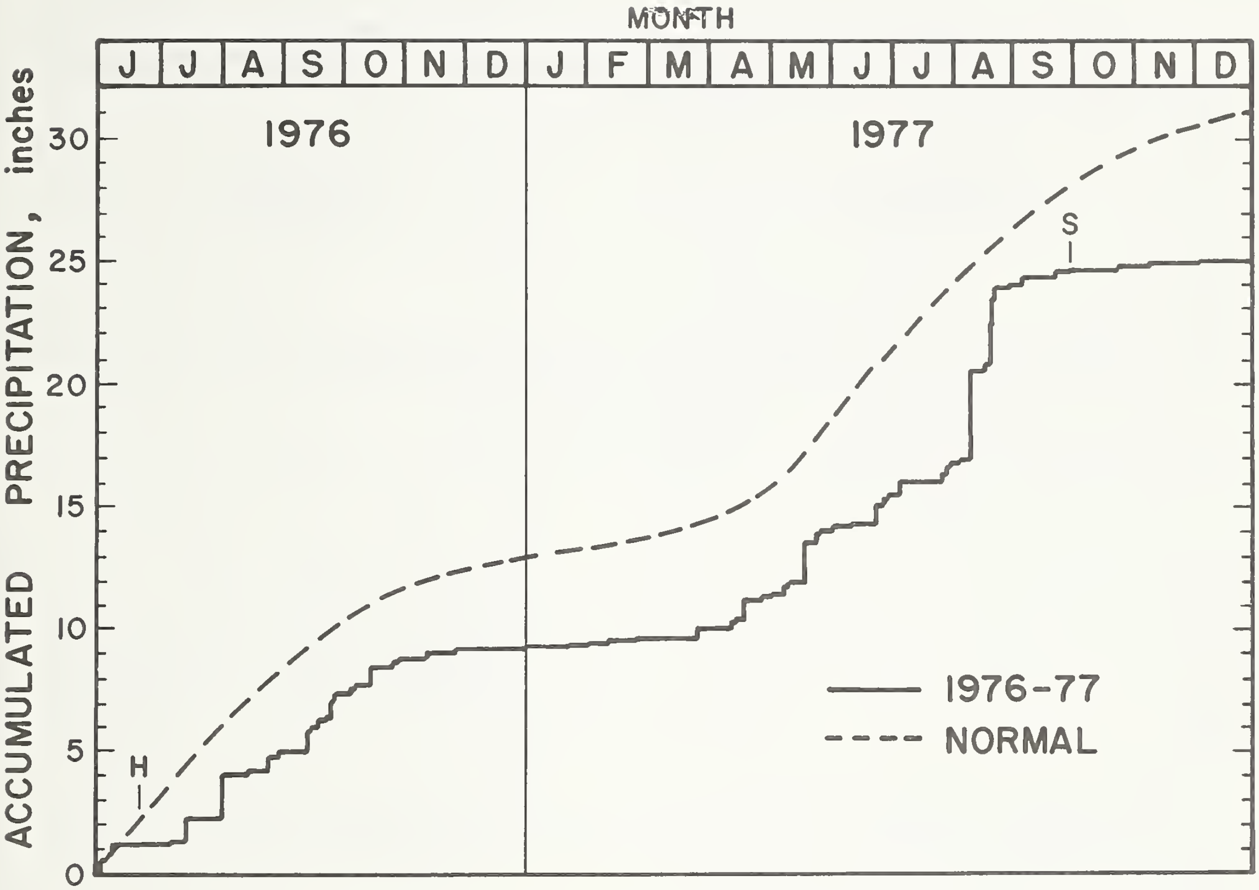

FIGURE 39.—Normal and actual accumulated precipitation, 1976-77.

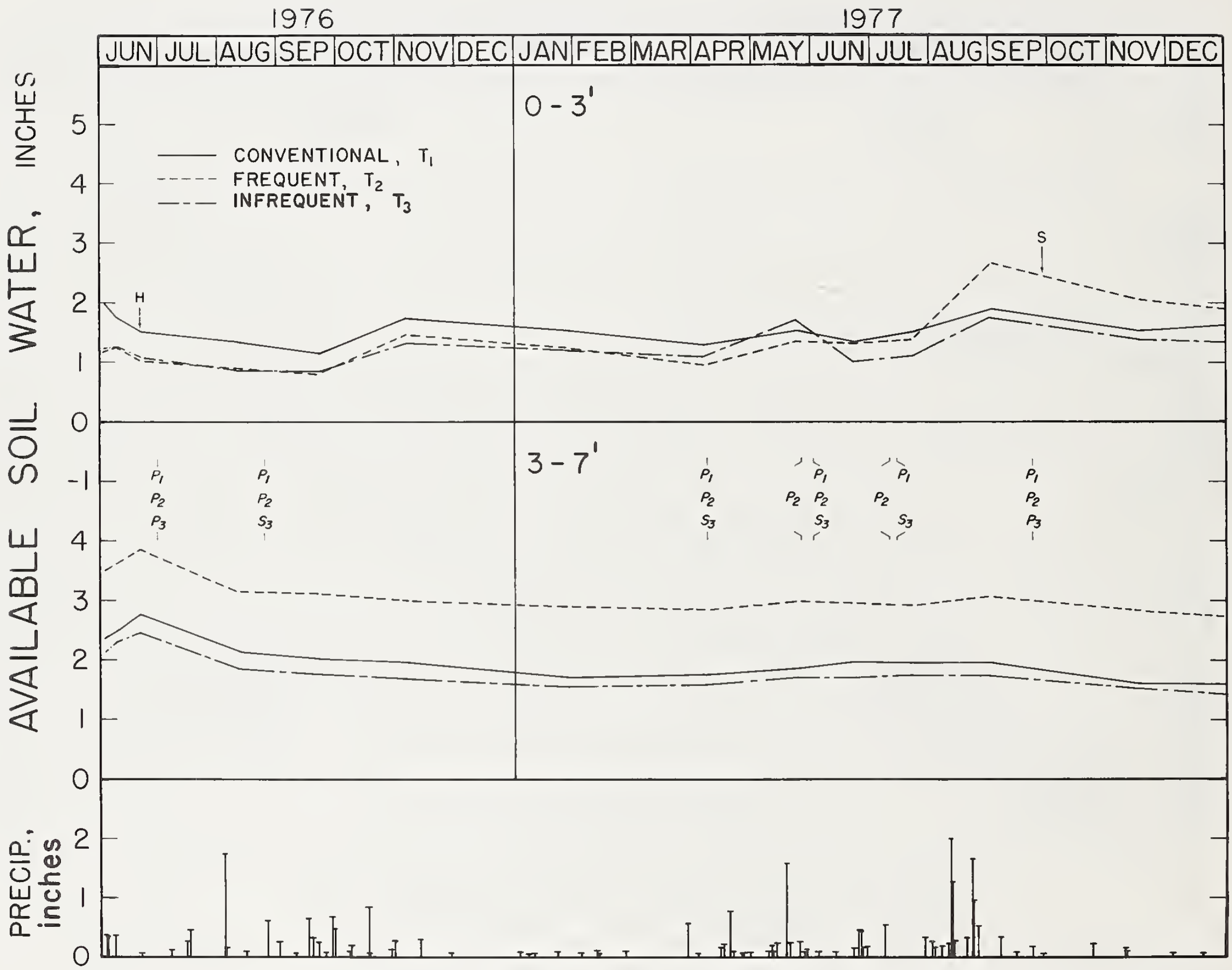

FIGURE 40.—Average available soil water and plowing and spraying dates by tillage treatment, block I (in fallow), 1976-77.

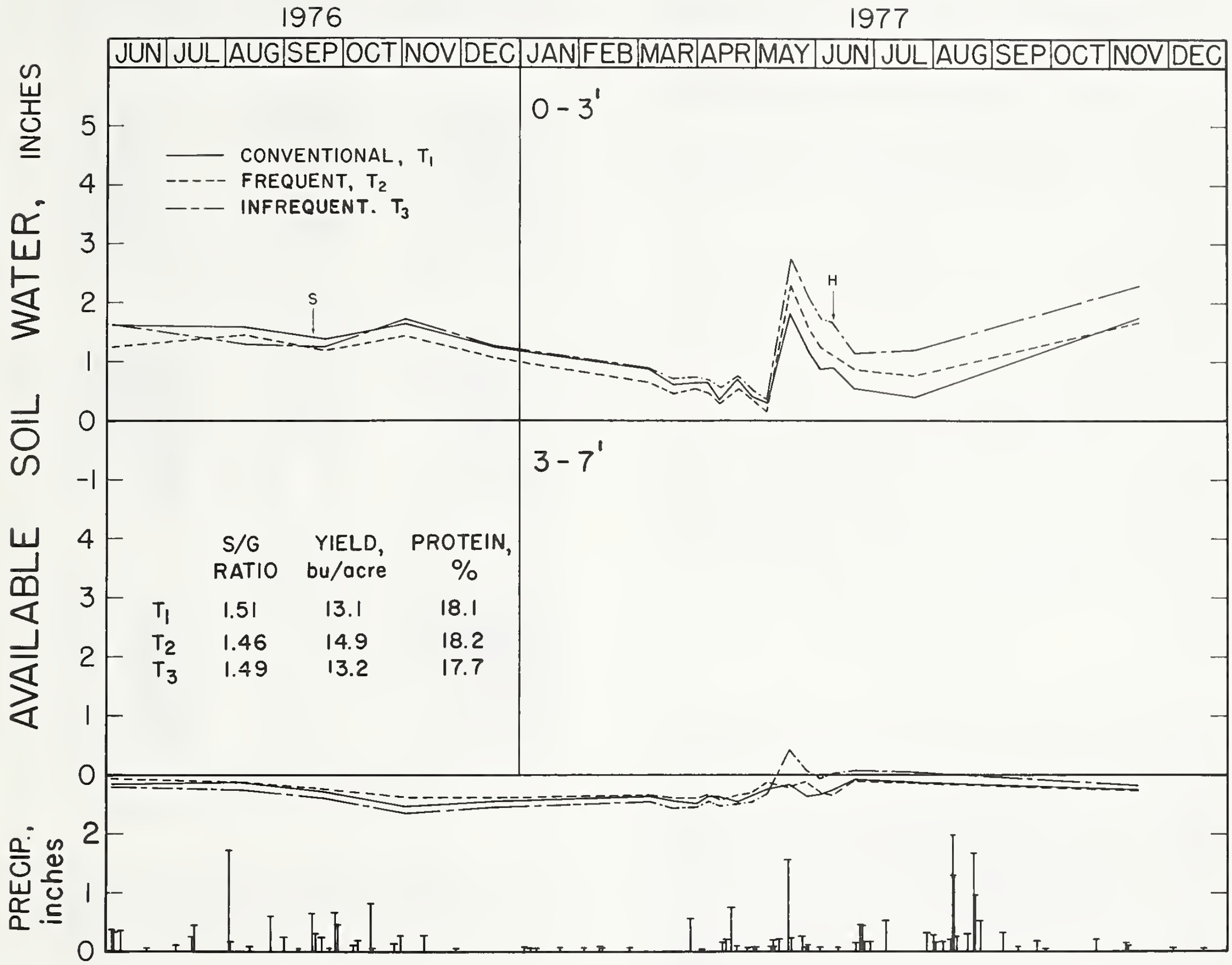

Figure 41.—Average available soil water, straw-grain (S/G) ratio, average crop yield, and average protein content by tillage treatment, block II (in wheat), 1976-77.

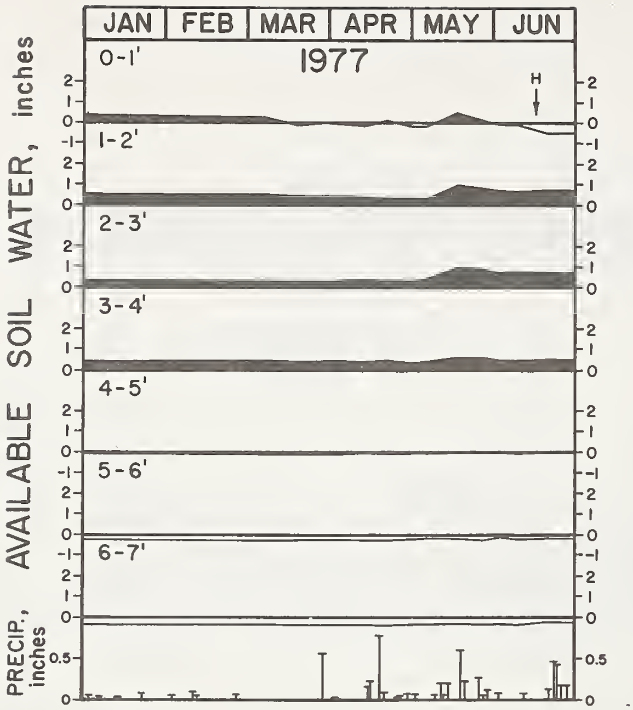

FIGURE 42.—Average available soil water by 1-foot-depth increments, block II (in wheat), 1977.

FIGURE 43.—Making soil water measurements after hand-sampling four center rows of wheat, block II, 1977. Average yield was 13.7 bushels per acre.

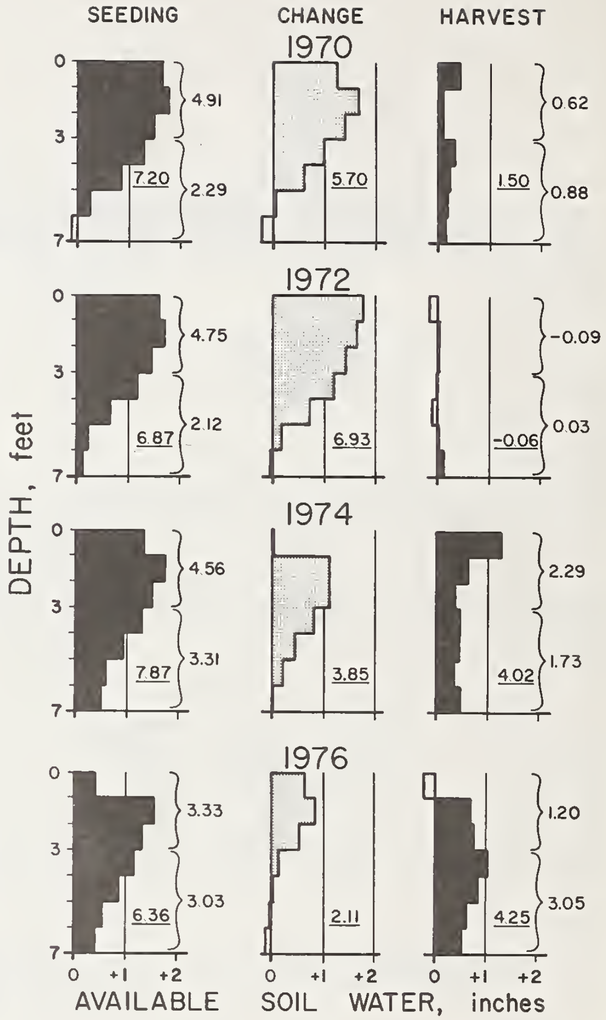

FIGURE 44.—Profiles of available soil water at seeding and harvest and of change from seeding to harvest, block I. Total inches of available water in the zero- to 3-foot, 3- to 7-foot, and zero- to 7-foot soil zones are given on right side of each profile.

inches. Figure 42 shows the available water content of individual 1-foot soil layers for the 1977 crop from January 1 to June 30. The 1977 crop subsisted mostly on water from the top foot of soil as it became available from rainfall. Only slight use was made of water from the second foot of soil, and none was used from below that depth. Several good rains in May added to the soil water through cracks to a depth of 4 feet, but because of a poor root system this water was not used to any extent by the crop.

In spite of extremely poor water conditions, the 1977 crop produced a fairly good grain yield that averaged 13.7 bushels per acre. The straw-

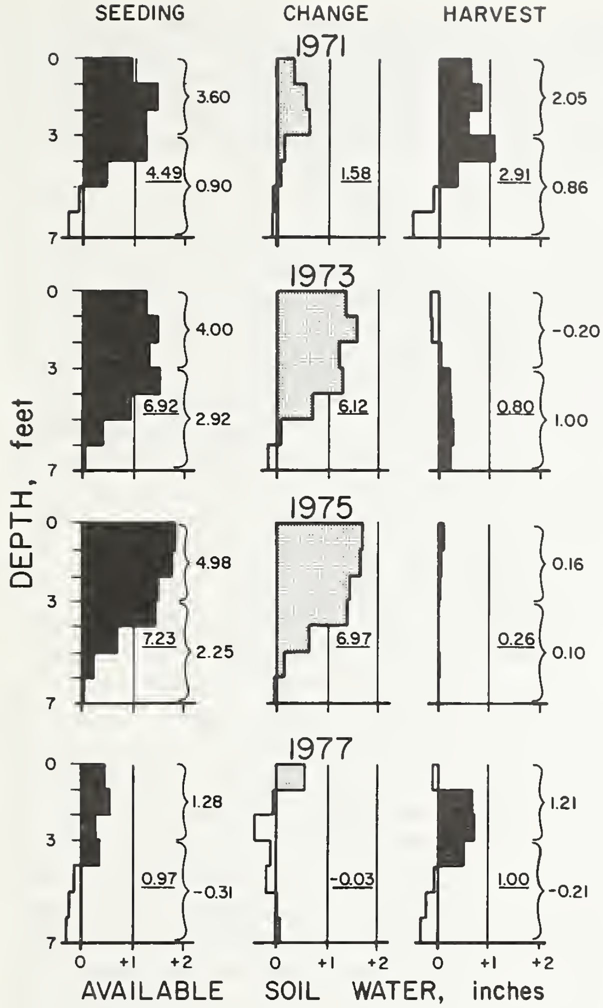

FIGURE 45.—Profiles of available soil water at seeding and harvest and of change from seeding to harvest, block II. Total inches of available water in the zero- to 3-foot, 3- to 7-foot, and zero- to 7-foot soil zones are given on right side of each profile.

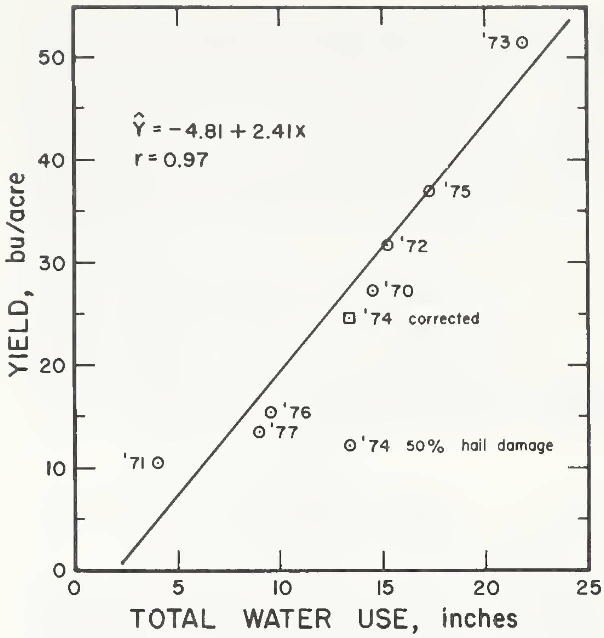

FIGURE 46.—Relationship between average grain yield and average total water use. The 1974 yield was not used in the analysis.

grain ratio averaged 1.49, the lowest of the eight crops (table 2). Figure 43 shows the appearance of the 1977 crop, which can be compared with that of the record-breaking 1973 crop (fig. 4).

Analyses of Grain Yield-Water Relationships

A linear-regression correlation analysis (Ostle 1954) was made of the relationship between the average grain yield for all treatments and the average total water use in different years, resulting in the equation

$$\hat{Y} = -4.81 + 2.41X, \quad (r = 0.97) \tag{3}$$

where X is total water use (soil water extracted from seeding to harvest plus growing period precipitation) in inches and $\hat{Y}$ is the estimated grain yield in bushels per acre (fig. 46). The hail-damaged crop of 1974 was not included in this analysis. The analysis indicates that the yield increase averaged 2.41 bushels per acre for each extra inch of total water use. Mathews and Brown (1938) made a similar regression analysis using pooled data from the Colby and Garden City, Kans., experiment stations. If this result is adjusted slightly to obtain an equal mean-equal variance solution comparable to equation 3 (Johnson 1959), we conclude that at these locations an extra inch of total water use increased the wheat yield by 2.62 bushels per acre.

A multiple-regression analysis was also made in which the average annual grain yield for all treatments was related to the average soil water use for all treatments and to the growing season precipitation, as separate independent variables, resulting in the equation

$$\hat{Y} = -4.60 + 2.70X_1 + 2.22X_2, \quad (R = 0.97) \tag{4}$$

where $\hat{Y}$ is the estimated yield in bushels per acre, X_1 is soil water use (seeding to harvest) in inches, and X_2 is the total growing season precipitation in inches. The 1974 yield was doubled for this particular analysis to allow for 50 percent hail damage. Equation 4 states that the increase in yield per extra inch of soil water used was greater than the increase per extra inch of growing season precipitation, 2.70 versus 2.22 bushels per acre. However, the standard partial-regression coefficient was greater for X_1 than for X_2, 0.59 versus 0.53, which indicates that the growing season precipitation was of greater importance than the soil water used in determining yield.

CONCLUSIONS

During the 10 years of this study, mid-September to mid-June growing season precipitation averaged 8.96 inches, compared to the longtime average of 10.80 inches at Bushland. Only the 1973 crop received more than the longtime average amount of growing season precipitation. However, the average grain yield of 24.9 bushels per acre for the 10 years is 1.25 times the longtime average grain yield of subtilled summer-fallowed wheat on the stubble-mulch plots of the Research Center.[5] The plots of these experiments may have had a small yield advantage as a result of having a zero slope, compared to the 0.5 percent slope on the stubble-mulch plots.

This study supplied convincing evidence of the need for fall precipitation if winter wheat is to develop an efficient root system. Four exceptionally high yielding crops (1970, 1972, 1973, and 1975) received above-average fall rains and later were able to extract water from at least a 5-foot soil depth. Conversely, three poor wheat crops (1971, 1976, and 1977) that were seeded in falls having below-normal rainfall were able to extract water from no deeper than 3 feet and thus failed to make full use of available soil water. We conclude that 6 feet is about the maximum depth from which wheat can extract water from Pullman clay loam. Also, the maximum amount of stored soil water that wheat can utilize from this soil is about 7 inches. The maximum amount of available stored water in the zero- to 3-foot soil zone at seeding was 4.98 inches in the fall of 1974. The maximum amount of available stored water in the zero- to 7-foot soil zone at seeding was 7.87 inches in the fall of 1973.

Sometimes conditions are such that, even though there is a considerable amount of available soil water at seeding, a crop may not be able to make much use of it because the plow layer is too dry to obtain an adequate stand or fall rainfall is too meager to allow the development of an extensive root system. For example, the 1978 crop failed to emerge because of dry soil conditions, even though the rainfall in August 1977 was 7.68 inches or 2.8 times normal. Cultivation and weeds dried out the plow layer in September, and too little rainfall occurred later to replenish the soil water. In another instance, the 1974 crop was seeded when the total available soil water was the greatest of this study, but a long dry period after seeding hindered root development and caused 4 inches of available water to be left in the soil at harvest. The largest soil water gains generally occurred in late spring, late summer, and early fall. Water storage was usually the result of heavy rains or a prolonged period with a concentration of moderately heavy rains. Water storage usually did not occur during the summer months, even though there was a large accumulation of rainfall, because high temperatures, weed growth, and cultivation caused high water loss. Soil water storage was progressive with depth, with little or no storage occurring below 3 feet until total available soil water in the zero- to 3-foot zone reached about 5 inches.

We found that minimum points of exhaustion of soil water can be highly variable even in a relatively uniform soil. The total unavailable water in 7 feet of soil at 18 individual access-tube locations along a line less than 200 feet in length in the block I test plots varied from 15.26 to 23.06 inches. This range in unavailable water of 7.80 inches was greater than the maximum amount of stored soil water that wheat is able to extract from 7 feet of soil during its growing season.

A few differences in water storage as a result of tillage treatments were observed. In general, however, the experimental treatments did not have a great effect on soil water conservation, and in no year did an analysis of variance show a significant effect, at the 5-percent level, of treatment on yield.

[5] The 35-year average yield of subtilled summer-fallowed wheat is 16.5 bushels per acre, but this includes six crop failures (Johnson and Davis 1972). The average yield for years without a crop failure is 20 bushels per acre.

As previously stated, a major goal of the study was to develop more precise procedures for measuring soil water. Using the rolling platform not only prevented damage to the crop when making water determinations, it also enabled regularly scheduled readings to be made in extremely wet soil. Also, the illustrations having average curves of total available water contents for the zero- to 3-foot and 3- to 7-foot soil zones show that significant progress toward this goal was made. The close agreement and excellent parallelism of the curves give evidence of a precision of measurement that is not realizable by gravimetric sampling or, in the authors' experience at least, by the commonly used methods with the neutron meter. The fact that the gradual process of water extraction from increasing soil depths as the wheat crops developed was monitored by weekly neutron meter readings is proof that even slight changes in soil water can be detected by the methods used in this study.

Because of the energy shortage, there is interest in reducing tillage frequency by chemical fallowing. This study indicated that chemical fallowing (infrequent tillage, T_3) can be substituted for tillage without reducing yield, the average yields for treatments T_1, T_2, and T_3 being 23.6, 25.7, and 25.4 bushels per acre, respectively. Chemical fallowing, because of fewer tillage operations, might be expected to reduce the nitrification rate of the soil and lower the protein content of the grain. However, during this study tillage frequency had a neglible effect on protein content. In 1976, a year in which the protein content was about average, the average contents for treatments T_1, T_2, and T_3 were 13.0, 13.2, and 12.5 percent, respectively. In 1977, a year in which the protein content of the wheat was outstandingly high, the average protein contents were 18.1, 18.2, and 17.7 percent for T_1, T_2, and T_3, respectively. The high protein content in 1977 may have been the result of a thorough drying-out of the soil by the 1975 crop, a process that is known to increase the nitrification rate of a soil.

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